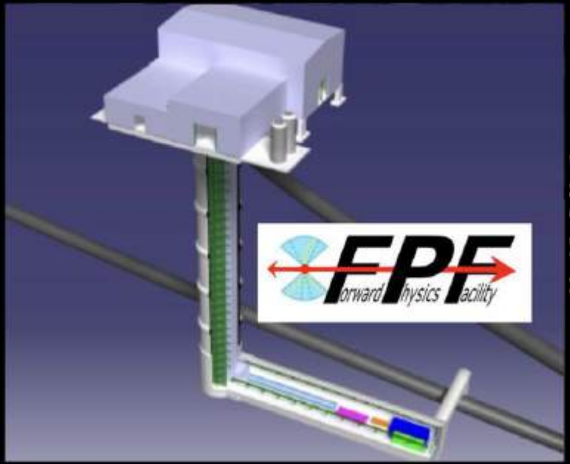
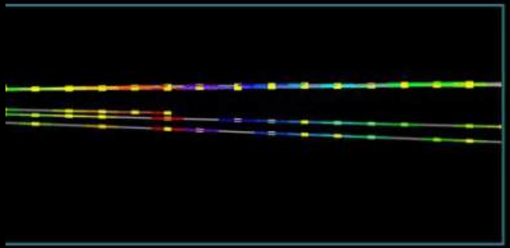
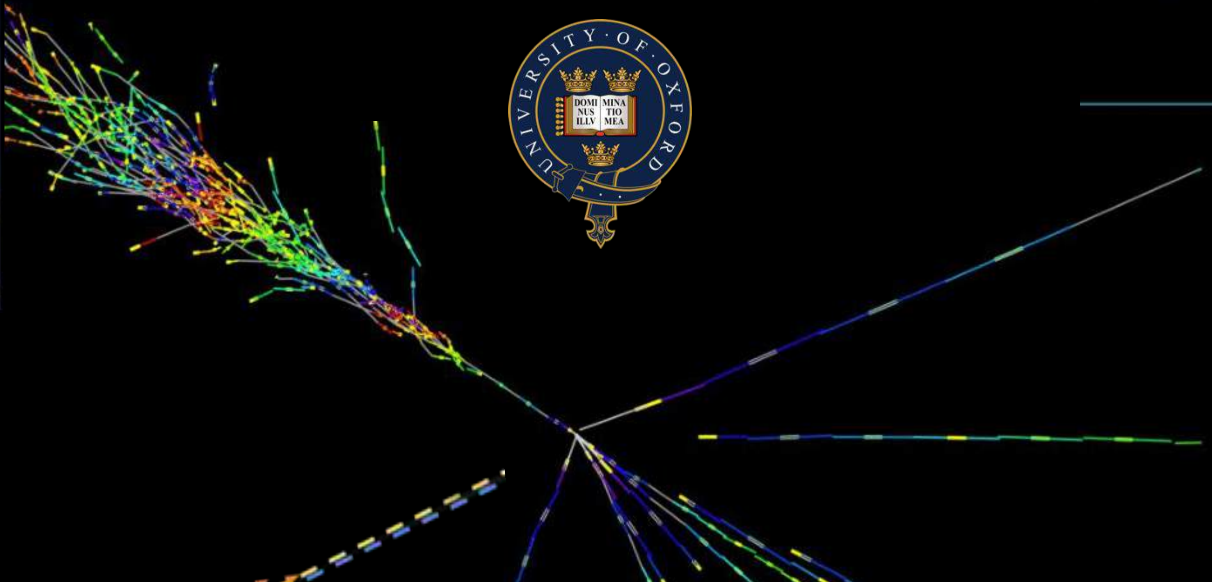
FPF @ LHC p1 & SHiP @ ECN3: The Science Case

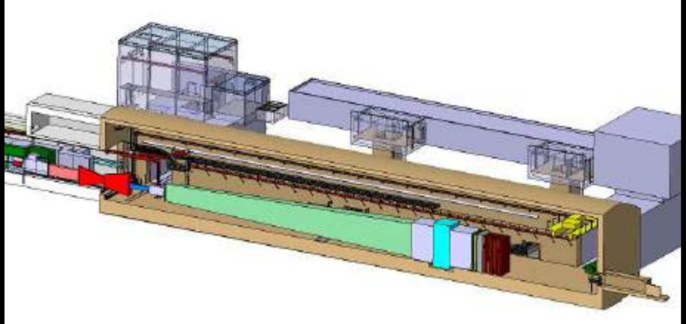
(Non-collider Experiments – Neutrinos: QCD / BSM / Astroparticle)

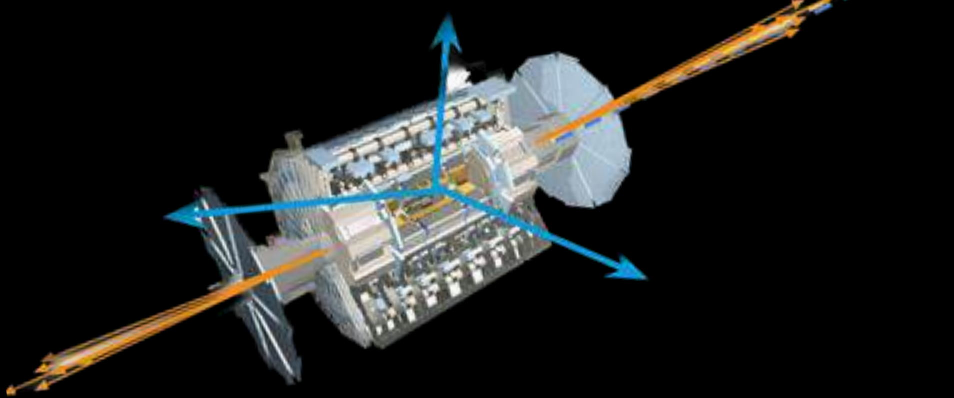


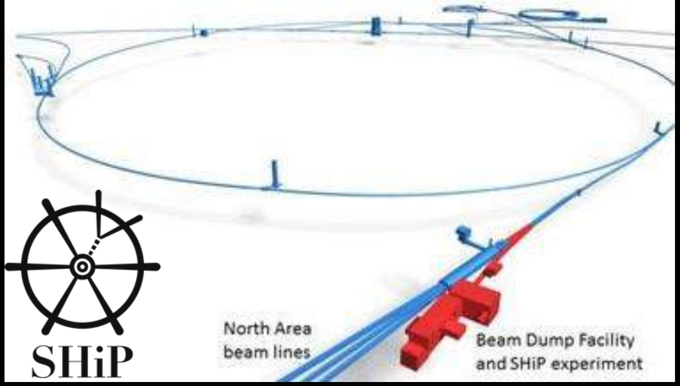
Subir Sarkar





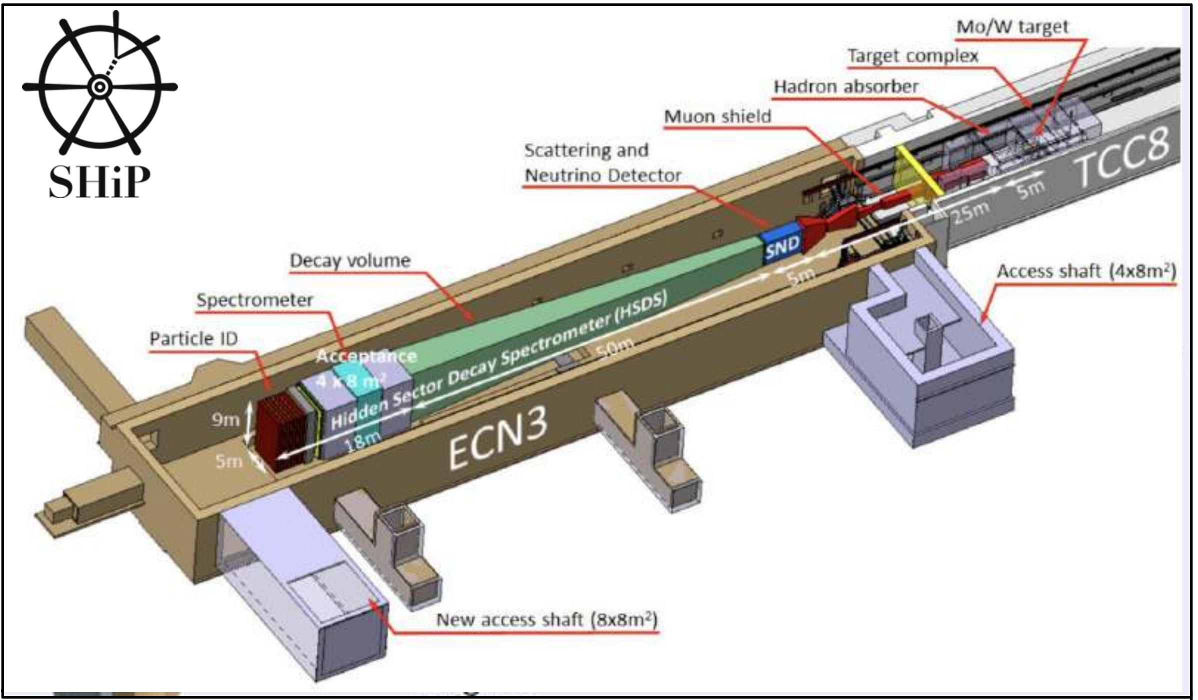


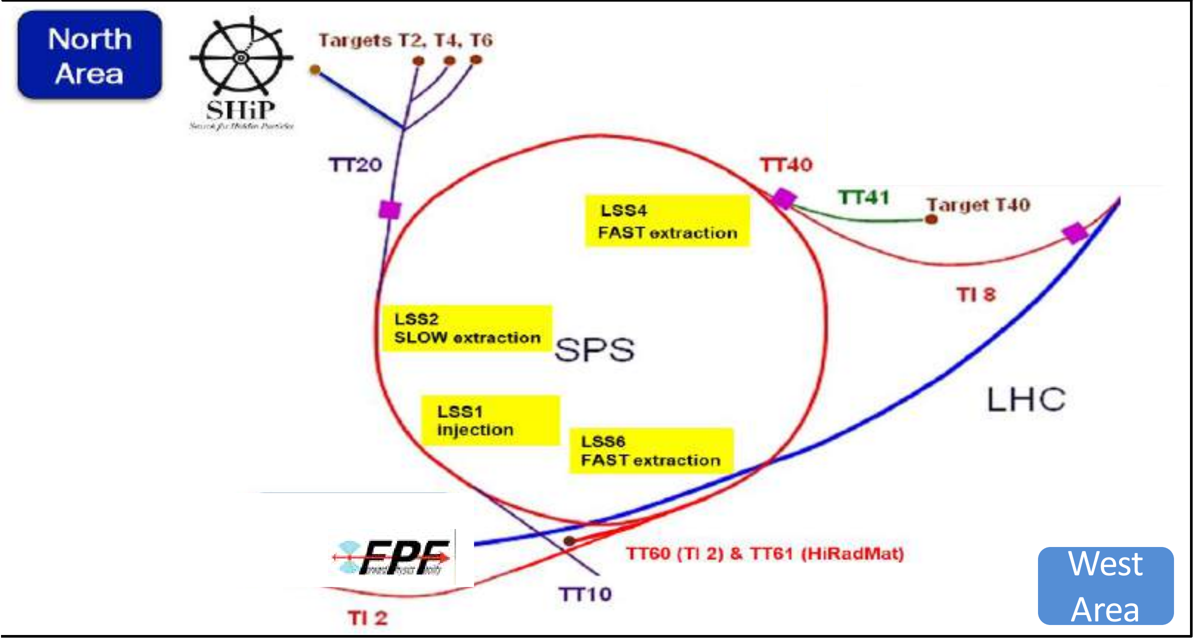




ECFA-UK Meeting, Durham, 23-26 Sept 2024

The renaissance of neutrino experiments @ CERN – at both the SPS & the LHC





2016

- ➢ Proposal for ‘Search for hidden particles’ (SHiP) @SPS
- ➢ Physics Beyond Colliders (PBC) initiative launched

2018

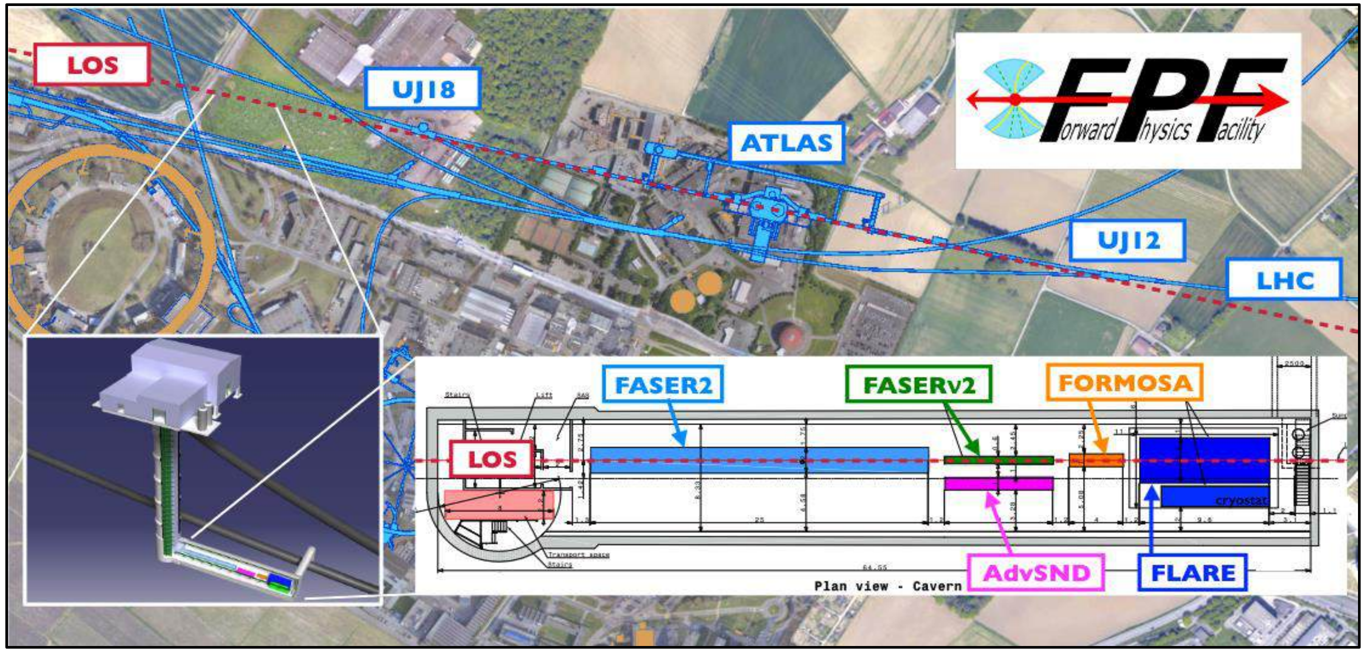
- ➢ FASER proposed to detect neutrinos from LHC P1

2023

- ➢ Detection of collider neutrinos by FASERν & SND@LHC

2024

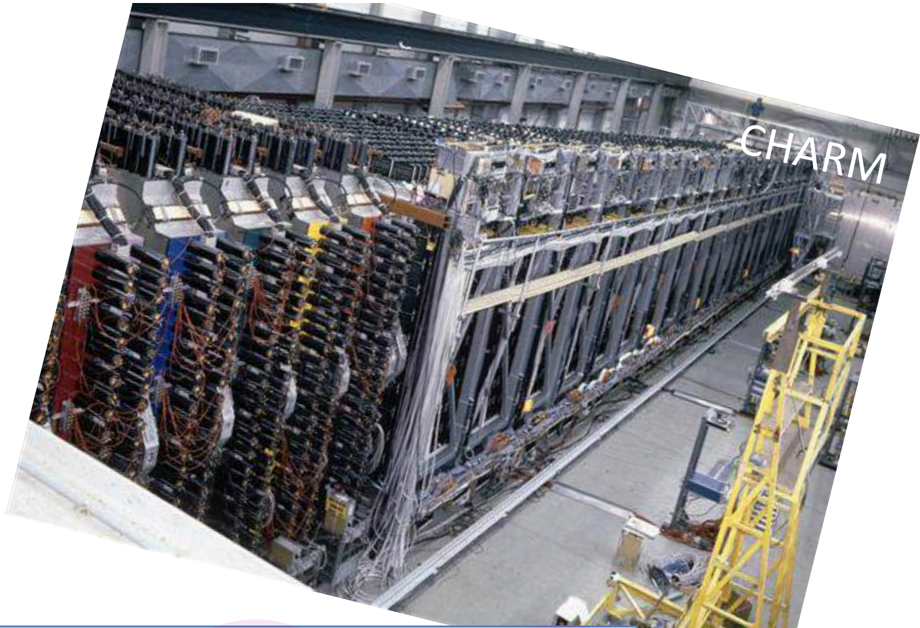
- ➢ SHiP approved for construction
- ➢ Awaiting decision on Forward Physics Facility (FPF) @ LHC



The 1970's-80's were a glorious era of pioneering neutrino experiments @ CERN


CDHS


BEBC


CHARM

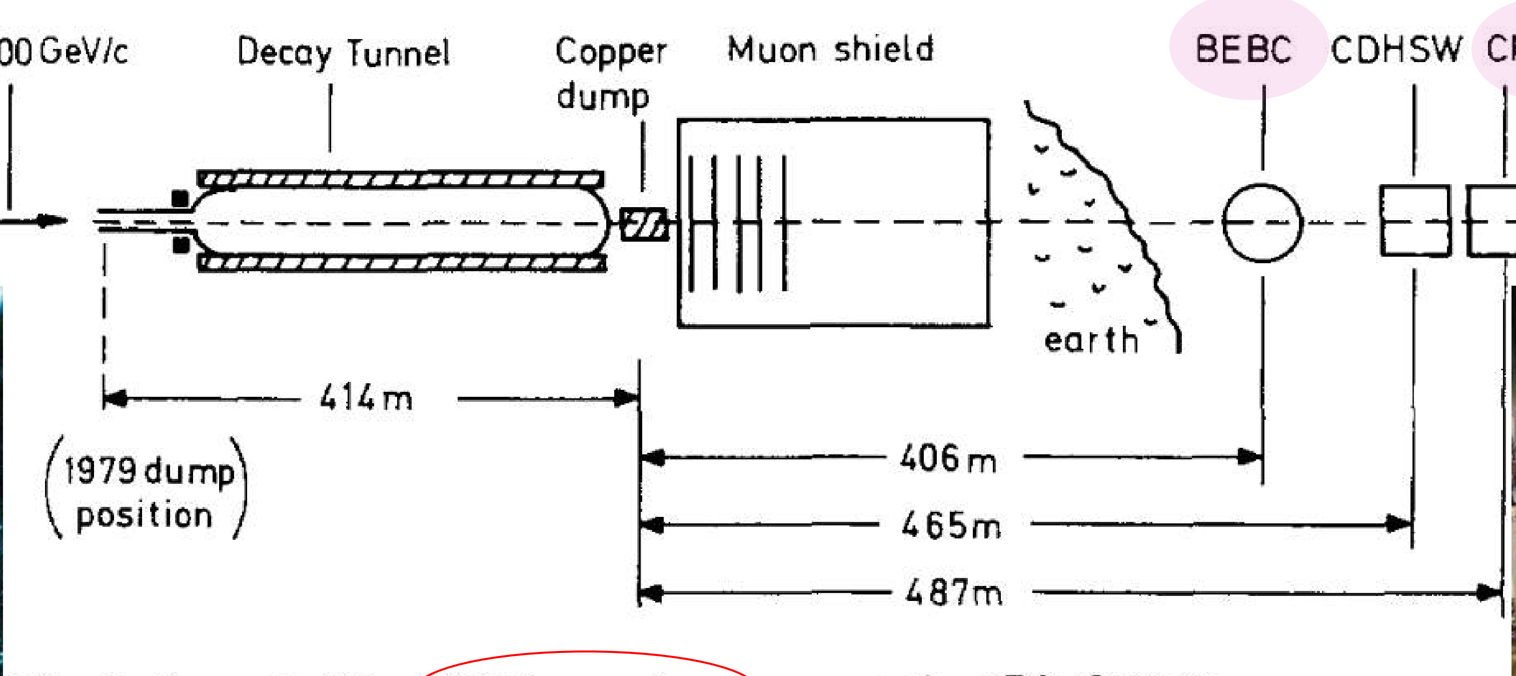


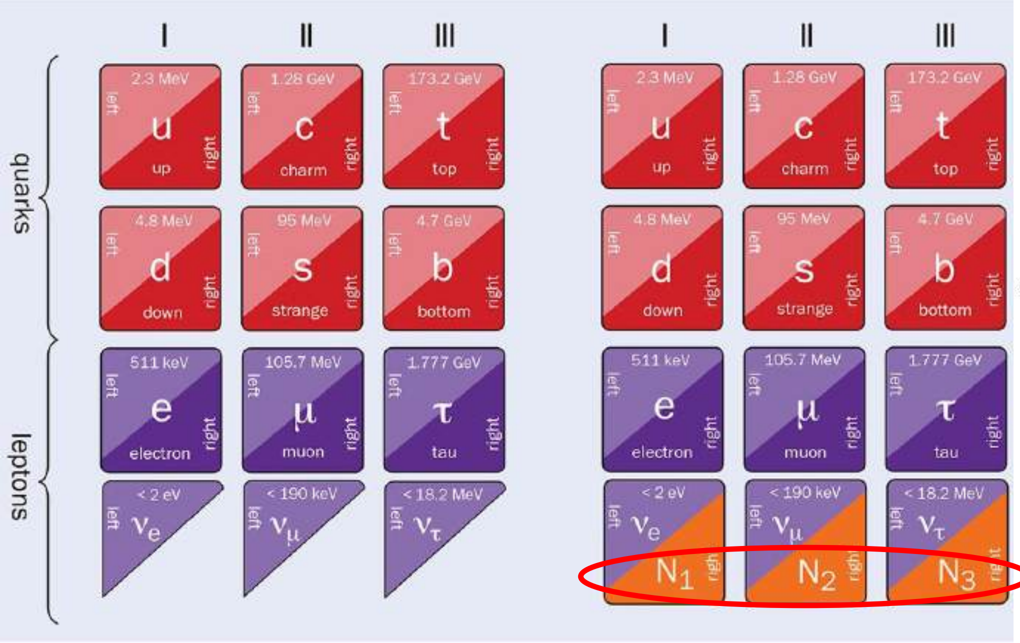
Fig. 1. Layout of the 1982 beam-dump area at the SPS, CERN.

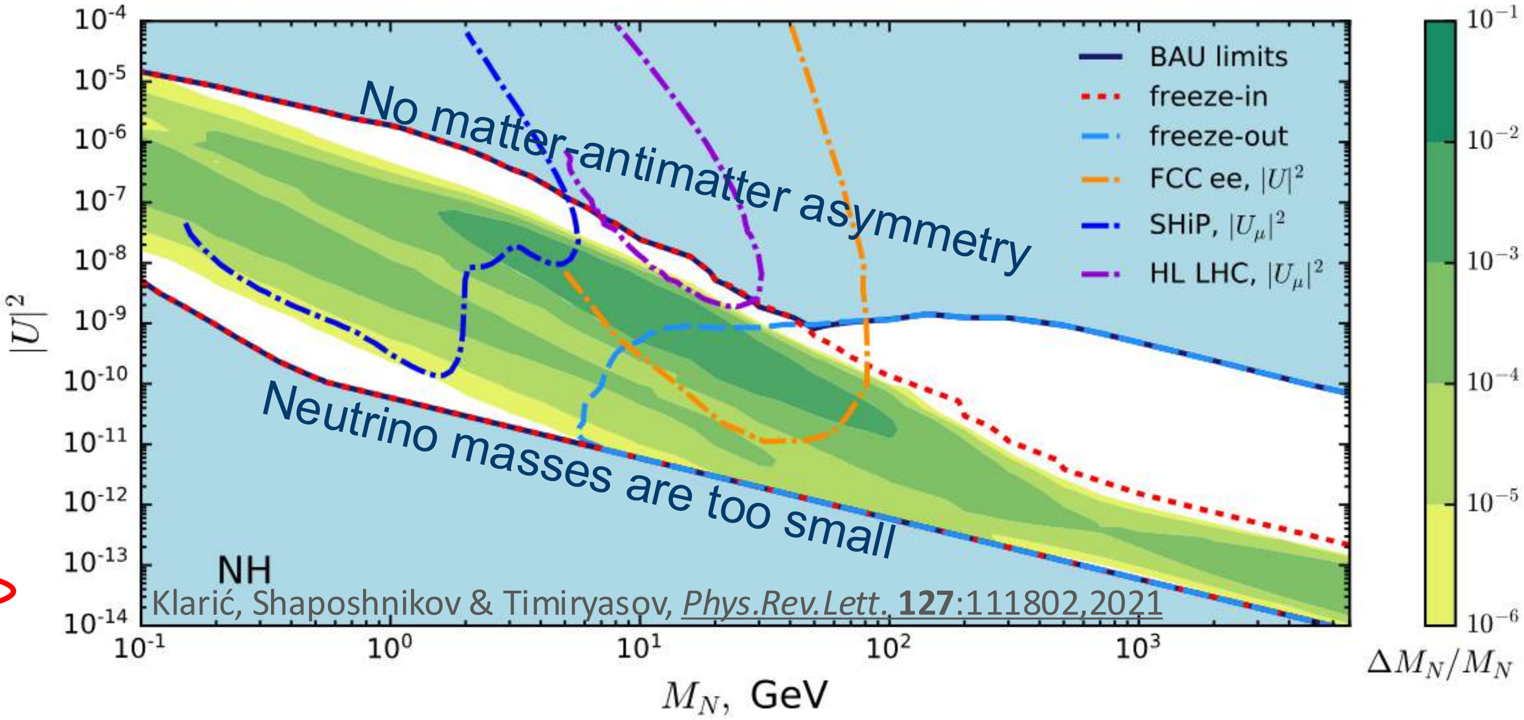

1st neutral current event, 1973


Gargamelle

Subsequently neutrino oscillations were discovered … *first* sign of physics beyond SM

The simplest renormalisable extension of the SM which contains this, contains right-handed (RH) neutrinos





No matter-antimatter asymmetry

Neutrino masses are too small

Klarić, Shaposhnikov & Timiryasov, *Phys.Rev.Lett.* **127**:111802,2021

If in addition to (lepton-number conserving) Dirac masses due to interaction with the Higgs field, the RH neutrinos have (lepton-number *violating*) Majorana masses, then they can, *in principle* (Asaka, Shaposhnikov, *Phys.Lett.B* **620**:17,2005):

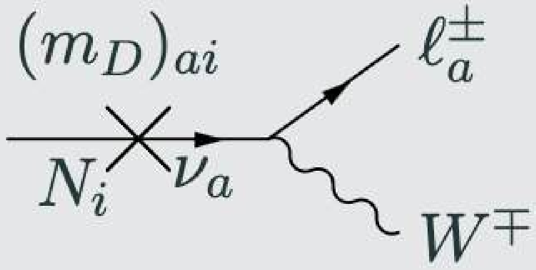
- Account for the baryon asymmetry of the Universe
- Provide a (warm) candidate for the dark matter

Test by searching for heavy neutral leptons (HNLs)
– SHiP@SPS, FPF@LHC (best below ~2 GeV)
– FCC, CEPC … (best above ~2 GeV)

Active neutrino masses

$$m_\nu = -m_D M_M^{-1} m_D^T$$

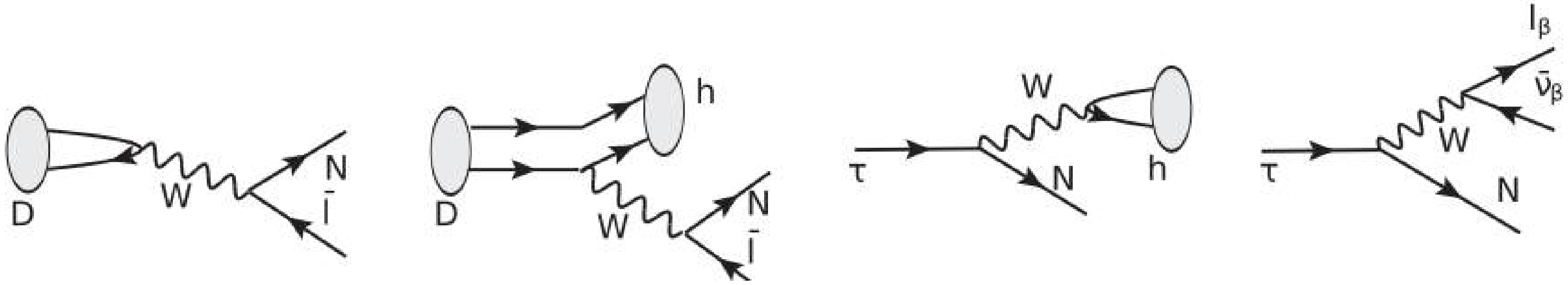
HNL mixing



$$U_{ai}^2 \equiv \left|\left(m_D M_M^{-1}\right)_{ai}\right|^2$$

$$U^2 = \sum_{a,i} U_{ai}^2$$

Heavy Neutral Leptons: Production & Decay



$$L_{lab,N} \simeq 30 \left(\frac{10^{-3}}{|U_{\tau 4}|^2}\right)\left(\frac{E_N}{10\ \text{GeV}}\right)\ \text{m}$$

$$\textbf{For}\ \begin{cases} m_N \sim 1\ \text{GeV} \\ |U_{e4}| = |U_{\mu 4}| = 0 \end{cases}$$

Consider production in the beam dump of charmed mesons – decaying promptly to neutrinos whose mixings create a beam of HNL that decay in into **opposite sign charged charged particles** (*eeν*, *eμν*, *μμν*, or *eπ*, *μπ*)

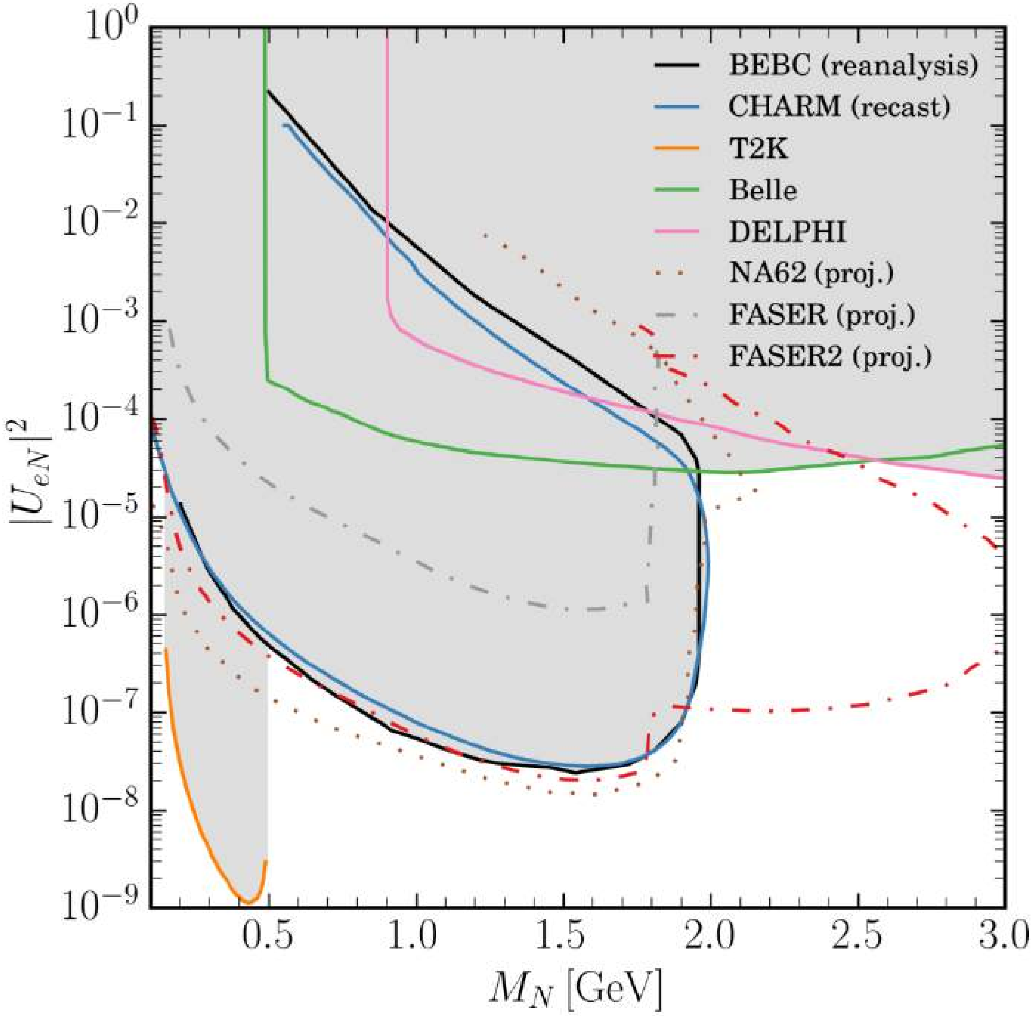
The number of HNLs produced, $\mathcal{N}_N$, can be directly related to the total number of detected active neutrinos of a particular species, $\mathcal{N}_{\nu_\ell}$, via:

$$\frac{\mathcal{N}_N}{\mathcal{N}_{\nu_\ell}} \simeq \frac{\sum_i \sigma(pN \to P_i + X)\text{Br}(P_i \to N + Y)}{\sigma(pN \to D^+D^- + X)\text{Br}(D^\pm \to \ell\,\nu_\ell + X) + \sigma(pN \to D^0\bar{D}^0 + X)\text{Br}(D^0 \to \ell\,\nu_\ell + X)}$$

arXiv:2208.00416

The 40+ year old beam dump experiments @ CERN still provide *world-leading* sensitivity to HNLs

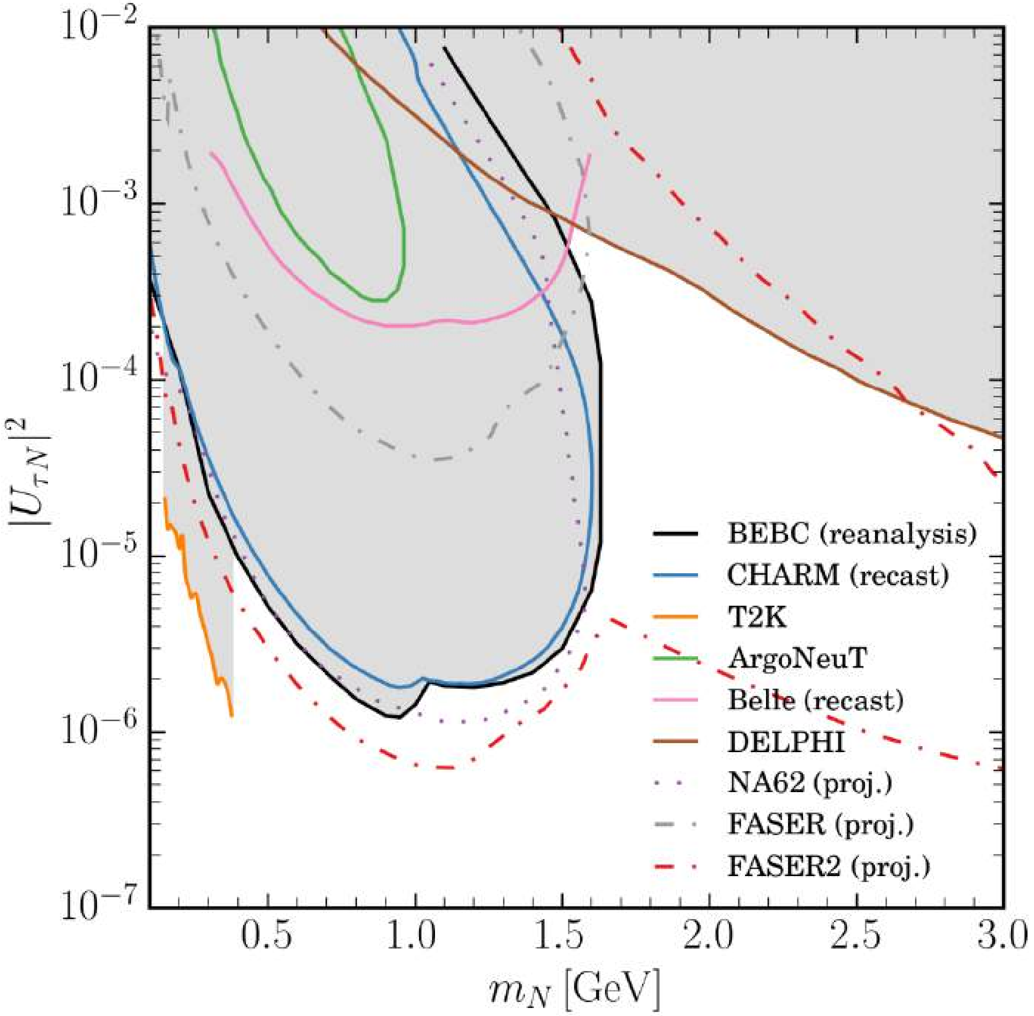
We revisit the search for heavy neutral leptons with the Big European Bubble Chamber in the 1982 proton beam dump experiment at CERN, focussing on those heavier than the kaon and mixing only with the tau neutrino, as these are far less constrained than their counterparts with smaller mass or other mixings. Recasting the previous search in terms of this model and including additional production and decay channels yields the strongest bounds to date, up to the tau mass. This applies also to our updated bounds on the mixing of heavy neutral leptons with the electron neutrino. Barouki, Marocco, S.S., *SciPost Phys.*__13__:118,2020 (Reanalysis of: Cooper-Sarkar *et al*, *Phys.Lett.*B__160__:207,1985)



Constraints on HNLs from BEBC & CHARM

FASER2 will do a factor of ~5 better up to m_c and a factor of ~100 better up to m_b

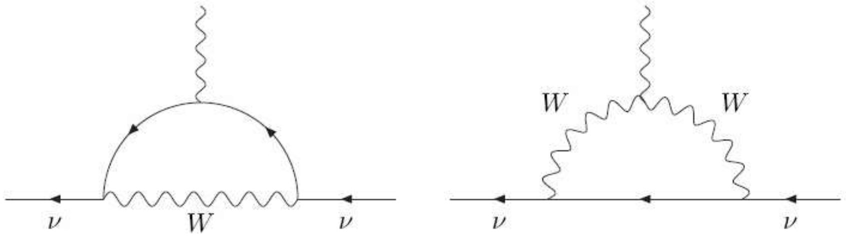
SHiP will do a factor of ~50 better upto m_c and a factor of ~1000 better upto m_b



"With more than 50k ν_τ CC interactions in the SND, SHiP can constrain the ν_τ magnetic moment down to $9 \times 10^{-8}\mu_B$"

SHiP Collaboration + BDF Working Group, *BDF/SHiP at the ECN3 high-intensity beam facility*, CERN-SPSC-2023-033

The magnetic moment expected for a Dirac neutrino is $\boldsymbol{\mu_\nu = 3\text{x}10^{-19}\,(m_\nu/\text{eV})\,\mu_B}$ but can be enhanced by BSM physics



Bound on the tau neutrino magnetic moment from the BEBC beam dump experiment

A.M. Cooper-Sarkar *et al*, Physics Letters B **280** (1992)153

Scattering by a magnetic moment is strongly forward-peaked, so we considered production from $D_s \rightarrow \tau\nu_\tau$ and looked for elastically scattered events within the forward cone defined by the maximum scattering angle

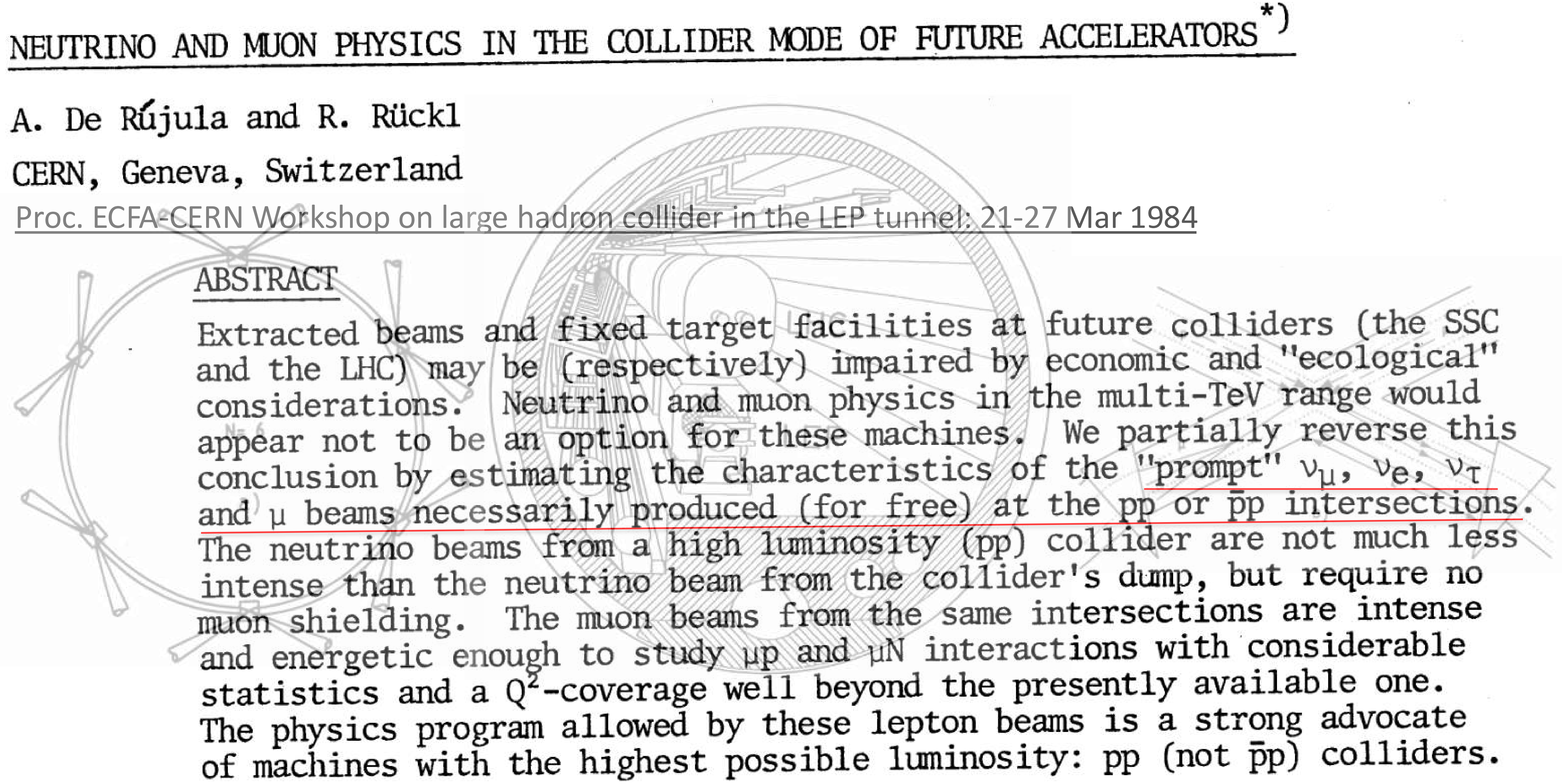
$$\frac{d\sigma_\mu}{dT_e} \simeq \pi r_e^2 \left(\frac{\mu_\nu}{\mu_B}\right)^2 \left(\frac{1}{T_e} - \frac{1}{E_\nu}\right) \qquad \sin^2\theta_{\nu e} = \frac{2m_e}{T_e + 2m_e}\left(1 - \frac{T_e}{E_\nu} - \frac{m_e T_e}{2E_\nu^2}\right), \quad \theta_{\nu e}^2 \lesssim 2m_e/E_e$$

We found 1 candidate event, *cf.* expected background of $0.5 \pm 0.1 \Rightarrow < 3.5$ events @ 90% CL

This implies a bound of $5.4 \times 10^{-7}\mu_B$ on the ν_τ magnetic moment

"*Those who cannot remember the past are condemned to repeat it.*" – George Santayana

LHC provides a collimated beam of TeV energy neutrinos in the far forward direction



NEUTRINO AND MUON PHYSICS IN THE COLLIDER MODE OF FUTURE ACCELERATORS*)

A. De Rújula and R. Rückl

CERN, Geneva, Switzerland

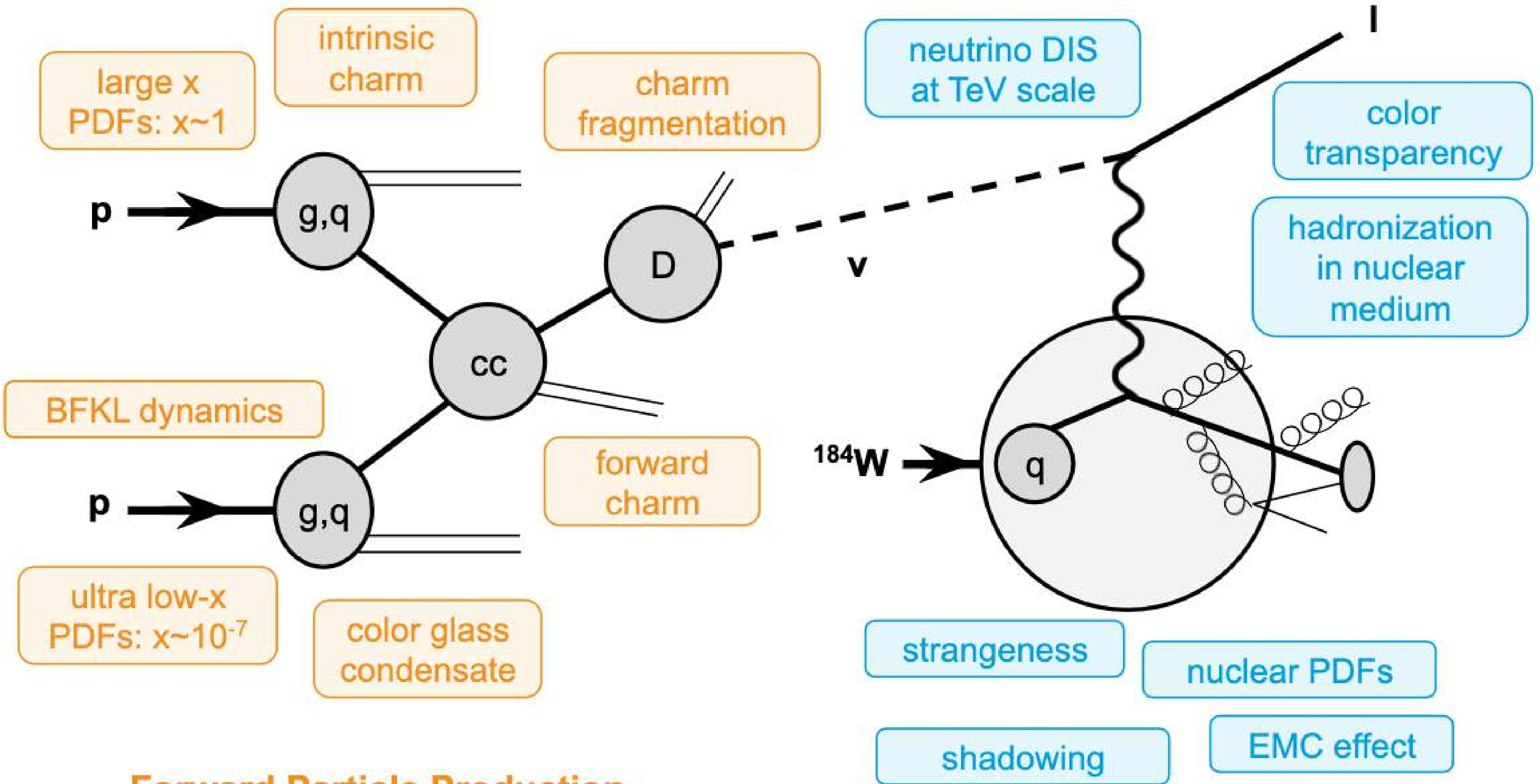
Proc. ECFA-CERN Workshop on large hadron collider in the LEP tunnel: 21-27 Mar 1984

ABSTRACT

Extracted beams and fixed target facilities at future colliders (the SSC and the LHC) may be (respectively) impaired by economic and "ecological" considerations. Neutrino and muon physics in the multi-TeV range would appear not to be an option for these machines. We partially reverse this conclusion by estimating the characteristics of the "prompt" ν_μ, ν_e, ν_τ and μ beams necessarily produced (for free) at the pp or $\bar{p}p$ intersections. The neutrino beams from a high luminosity (pp) collider are not much less intense than the neutrino beam from the collider's dump, but require no muon shielding. The muon beams from the same intersections are intense and energetic enough to study μp and μN interactions with considerable statistics and a Q^2-coverage well beyond the presently available one. The physics program allowed by these lepton beams is a strong advocate of machines with the highest possible luminosity: pp (not $\bar{p}p$) colliders.

… Forty years later, this vision is being realized

What can we do with an intense beam of TeV energy neutrinos?



large x PDFs: x~1

intrinsic charm

charm fragmentation

BFKL dynamics

forward charm

ultra low-x PDFs: x~10^{-7}

color glass condensate

neutrino DIS at TeV scale

color transparency

hadronization in nuclear medium

strangeness

nuclear PDFs

shadowing

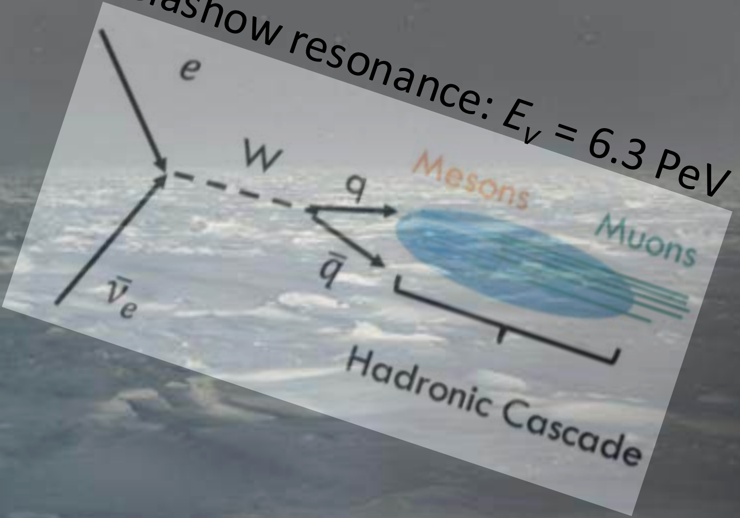
EMC effect

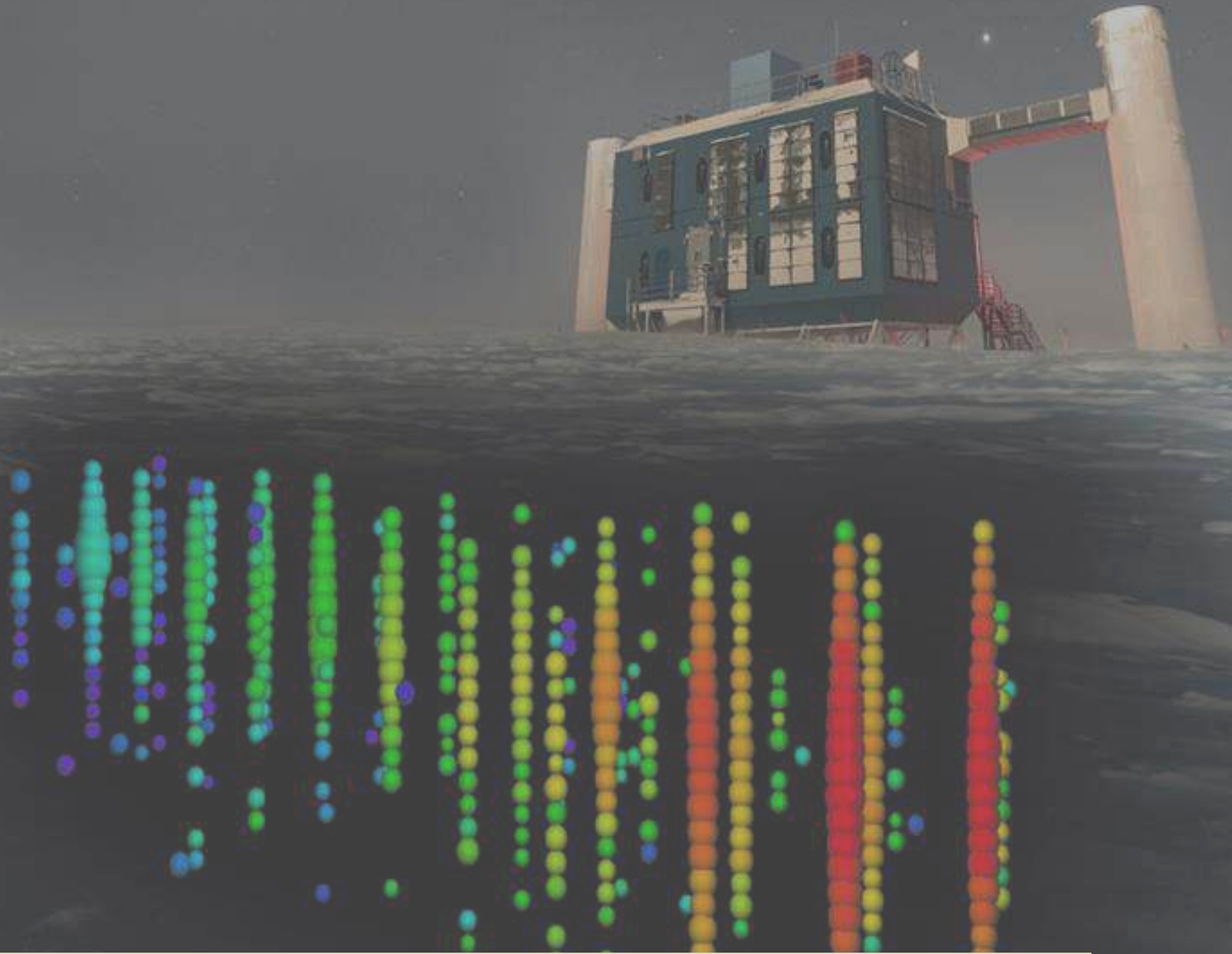
Forward Particle Production

Study interesting open issues in **QCD** – of relevance to **neutrino telescopes**; Study forward production of light hadrons – of relevance to **cosmic ray air shower arrays;** Search for **Beyond-Standard-Model** long-lived particles (axions, dark photons, heavy neutral leptons, milli-charged particles, scalar dark matter, quirks *etc*) – of relevance to **dark matter experiments.**

Feng *et al*, *J.Phys.G* **50**:030501,2023

Neutrino interactions, charm production …


Glashow resonance: $E_\nu = 6.3$ PeV

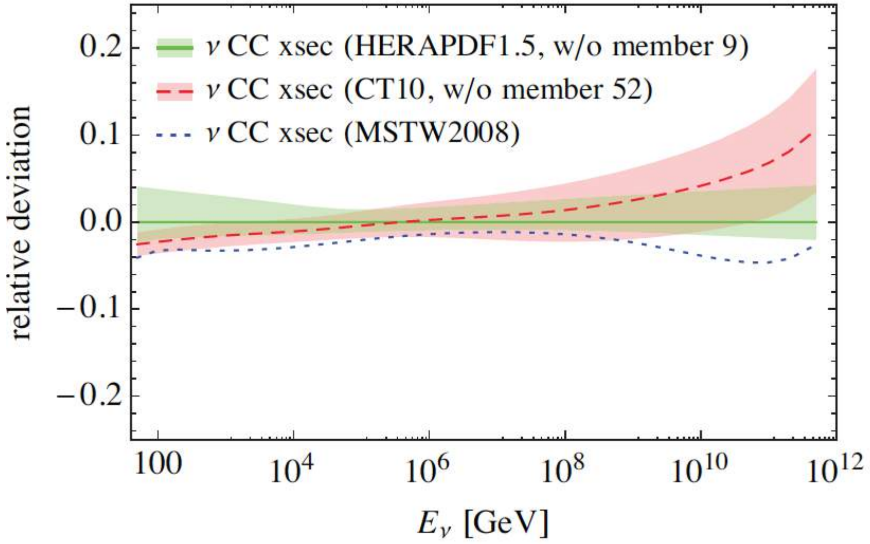


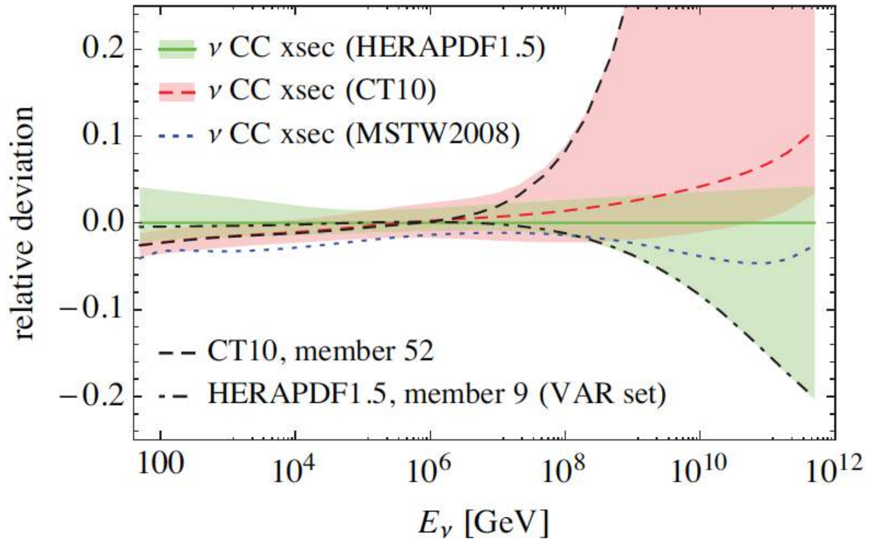
Synergy with Neutrino Telescopes

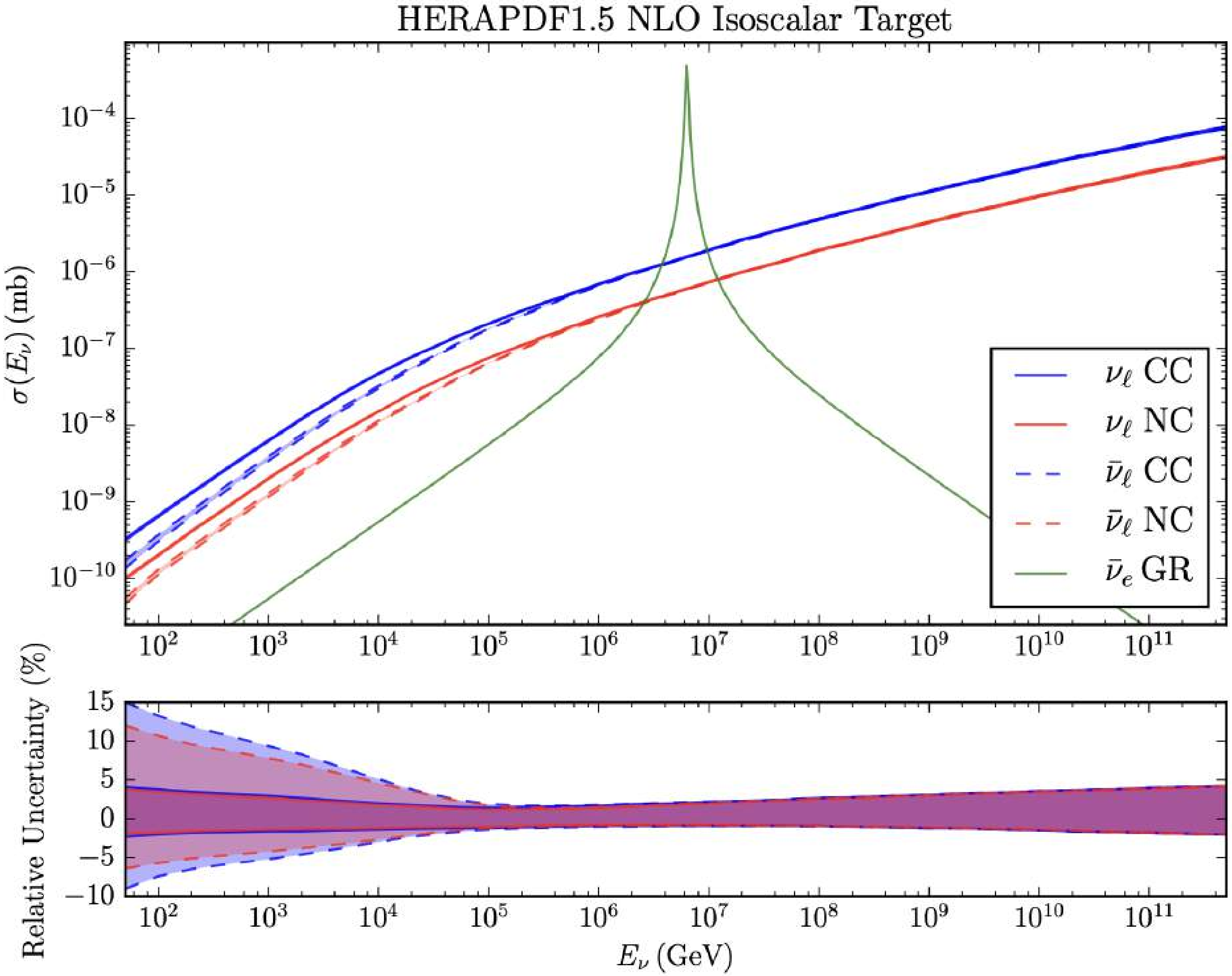
Antares/KM3NeT, **Baikal**/GVD, **IceCube**/Gen2, … P-One, Trident,
… **ANITA**, PUEO, GRAND, Trinity, … ARIANNA, ARA, RNO-G

The ν-*N* DIS #-secn. is an essential *input* for Neutrino Telescopes

IceCube use CSMS – a NLO calculation using HERAPDF1.5 (accurate to few %)
https://dispred.hepforge.org



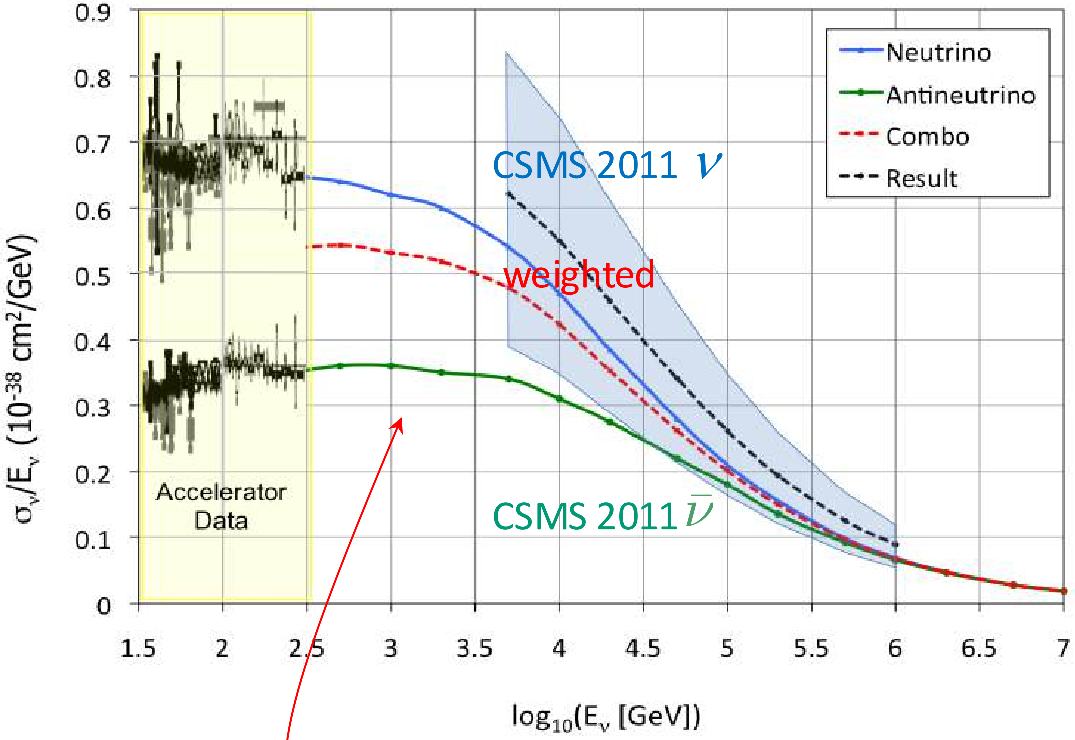


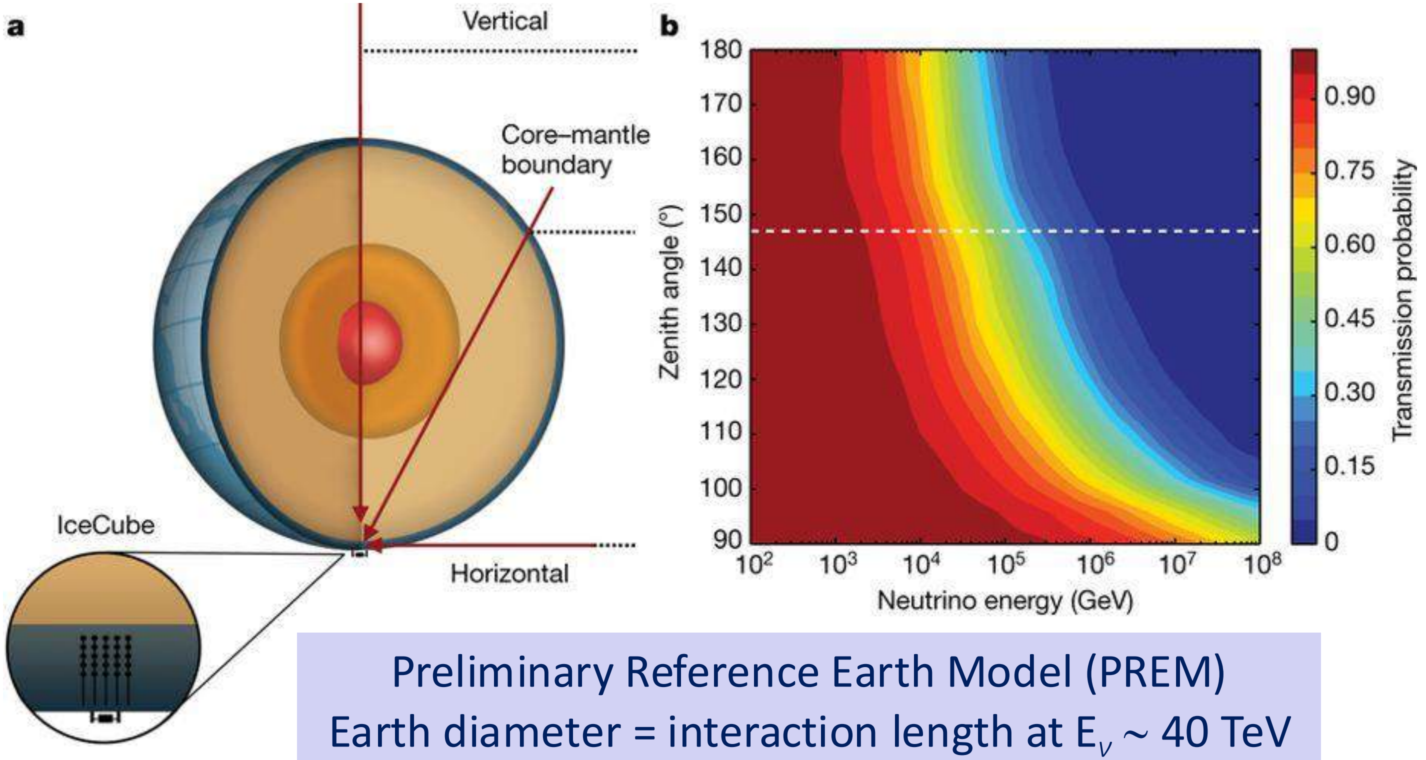


Cooper-Sarkar, Mertsch, S.S., *JHEP* **08**:042,2011 (CSMS)

There is good agreement between different PDF sets after rejecting *unphysical* members which would have yielded negative values for the structure function F_L (or violated the Froissart bound)

The predicted ν-N cross-section has been verified upto 10^3 TeV by ν absorption in the Earth





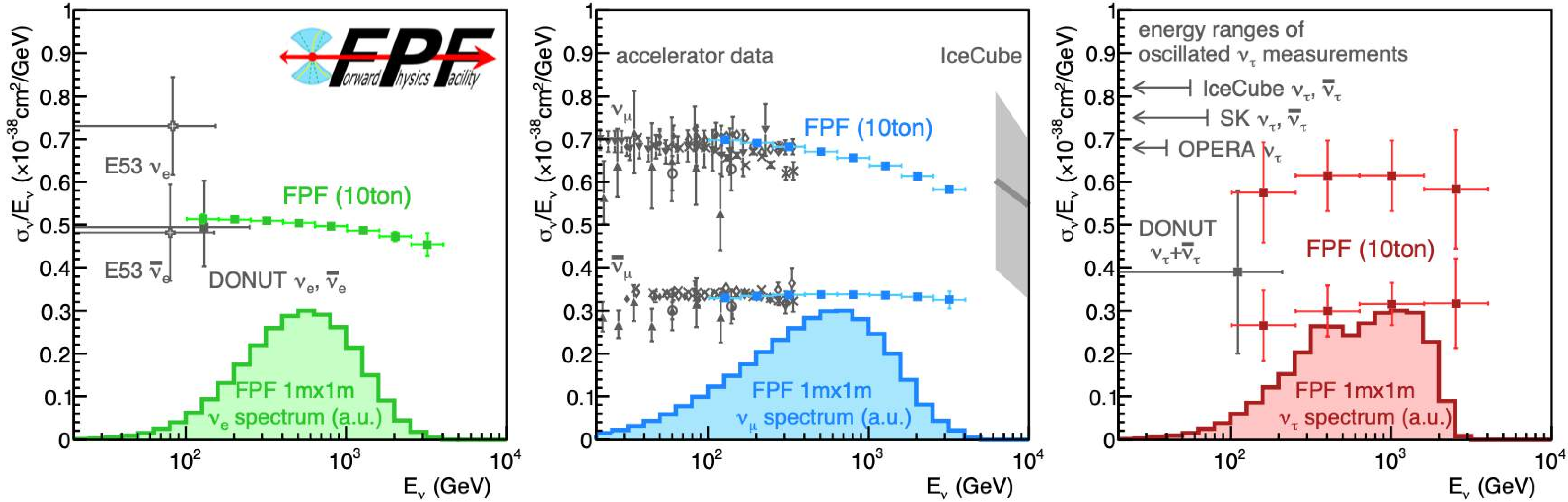
Preliminary Reference Earth Model (PREM)
Earth diameter = interaction length at E_ν ~ 40 TeV

IceCube Collaboration, *Nature* **551**:596,2017

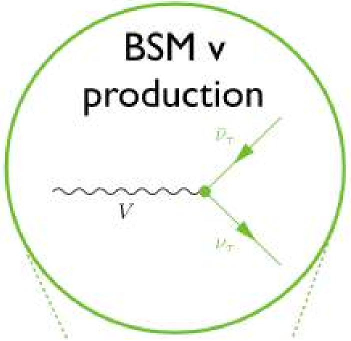
However, the measurement uncertainty is large (~30%) and the Earth absorption method works only above ~40 TeV

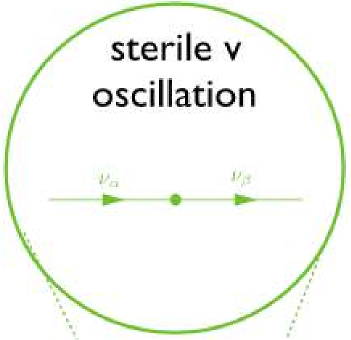
The FPF is well suited to bridge the gap between neutrino telescopes and measurements (upto ~350 GeV) at fixed-target experiments

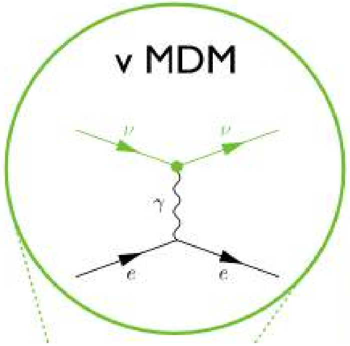
Neutrino flux as a function of energy for *e* neutrinos (left), μ neutrinos (middle), and τ neutrinos (right), with expected precision of FPF measurements (statistical uncertainties only)

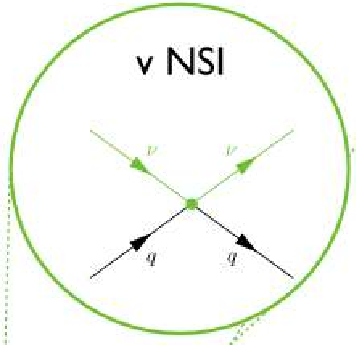


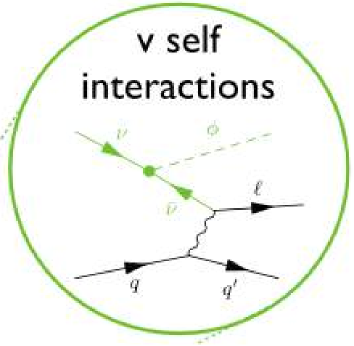
Feng *et al*, J.Phys.G**50**:030501,2023

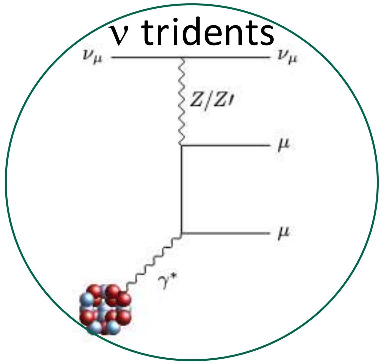








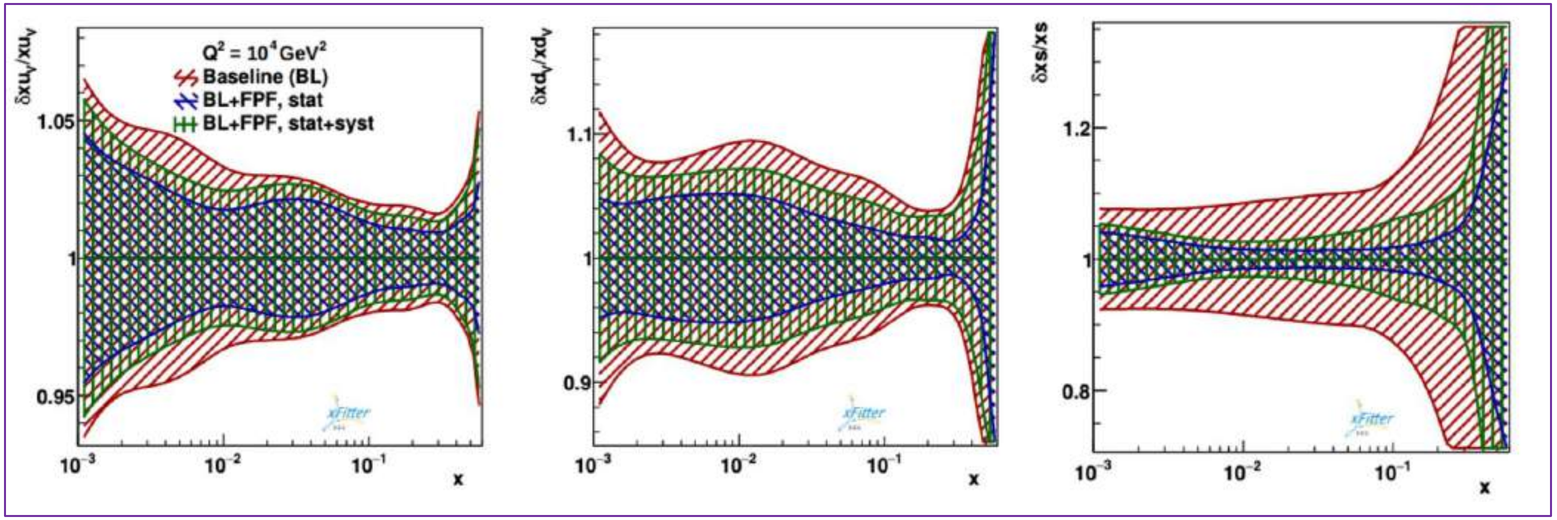


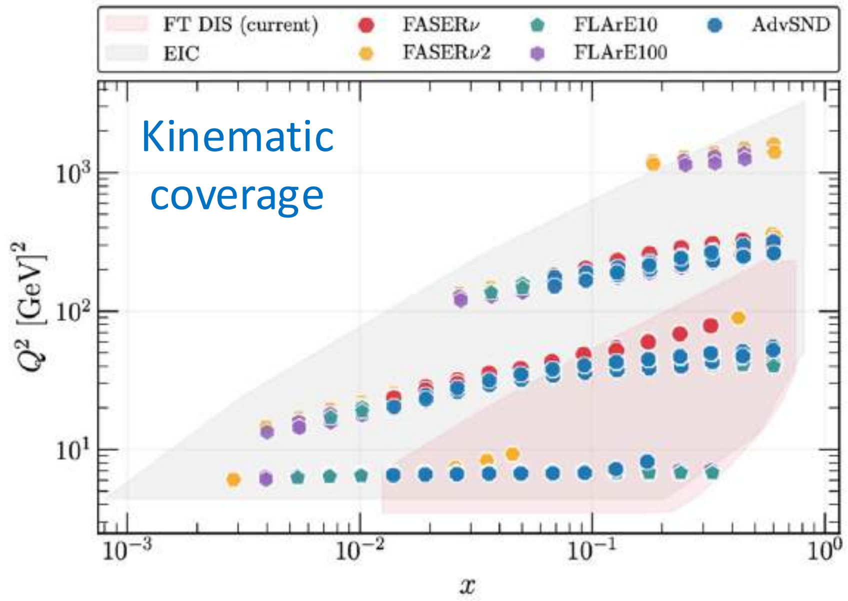


1406.16803

Can investigate many interesting BSM neutrino signatures too …

DIS @ FPF: Impact on proton PDFs

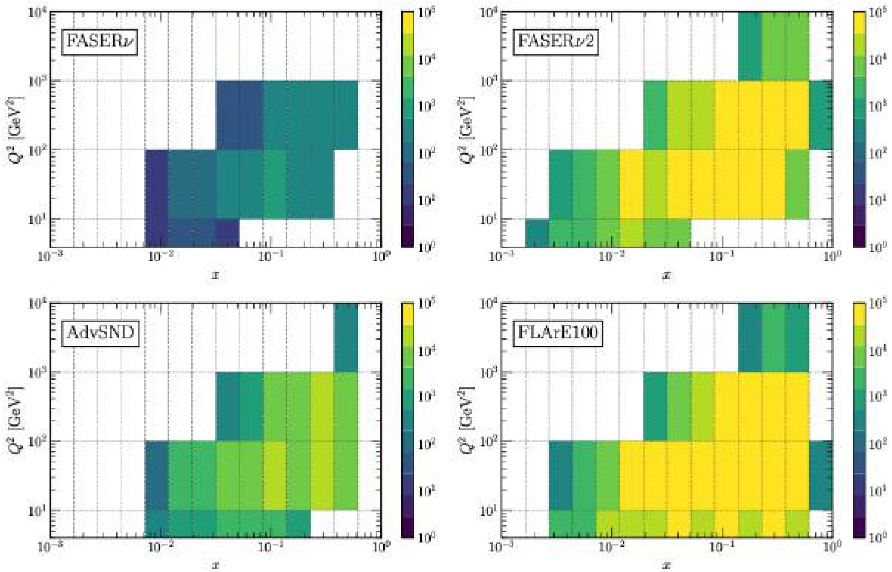




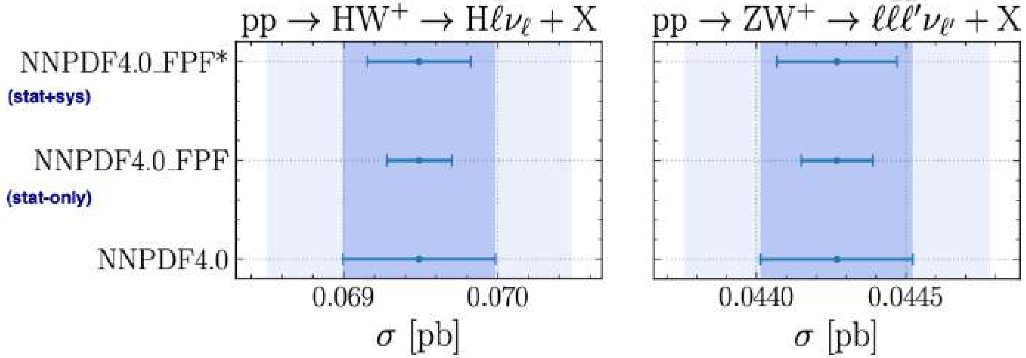
Kinematic coverage

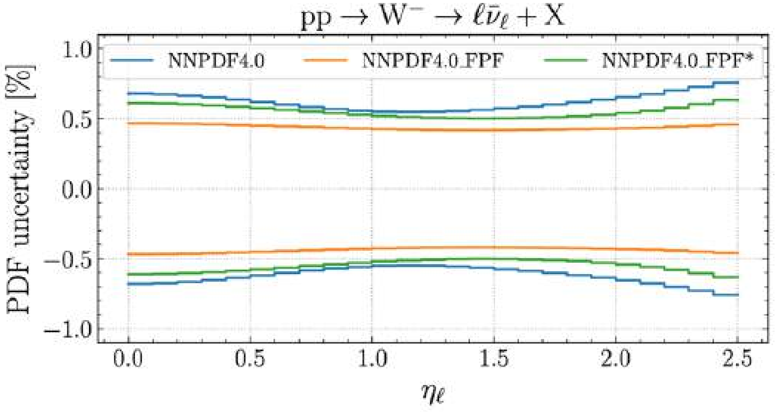
- ➢ Quantified by Hessian profiling of PDF4LHC21 (xFitter) and by direct inclusion in the global NNPDF4.0 Fit
- ➢ Most impact on up & down valence quarks, also on strange …
- ➢ PDFs thus improved enhance precision HL-LHC measurements

Event Yields



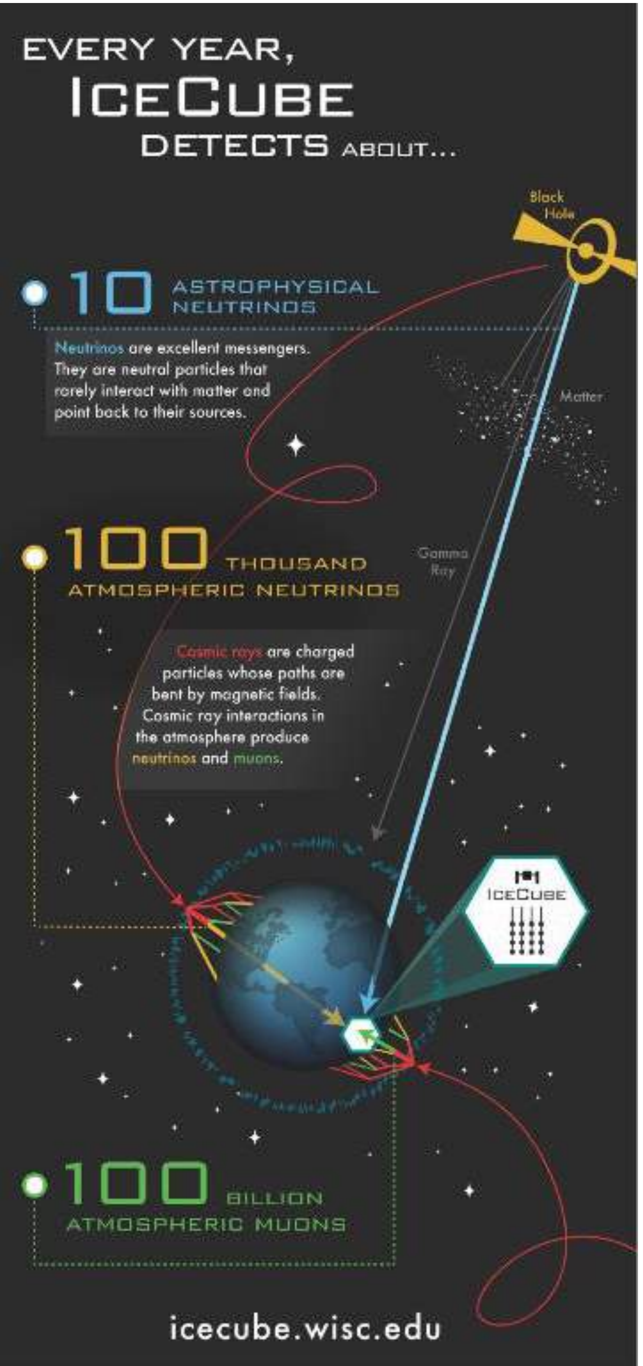
Cruz-Martinez *et al*, Eur.Phys.J.C**84**:369,2024





- Impact on **core HL-LHC processes** i.e. single and double weak boson production and Higgs production (VH, VBF)
- Also relevant for **BSM searches at large-mass** (via large-*x* PDFs)

Neutrino telescopes look for a cosmic signal buried in a huge background of atmospheric neutrinos



EVERY YEAR,
ICECUBE
DETECTS ABOUT…

10 ASTROPHYSICAL NEUTRINOS

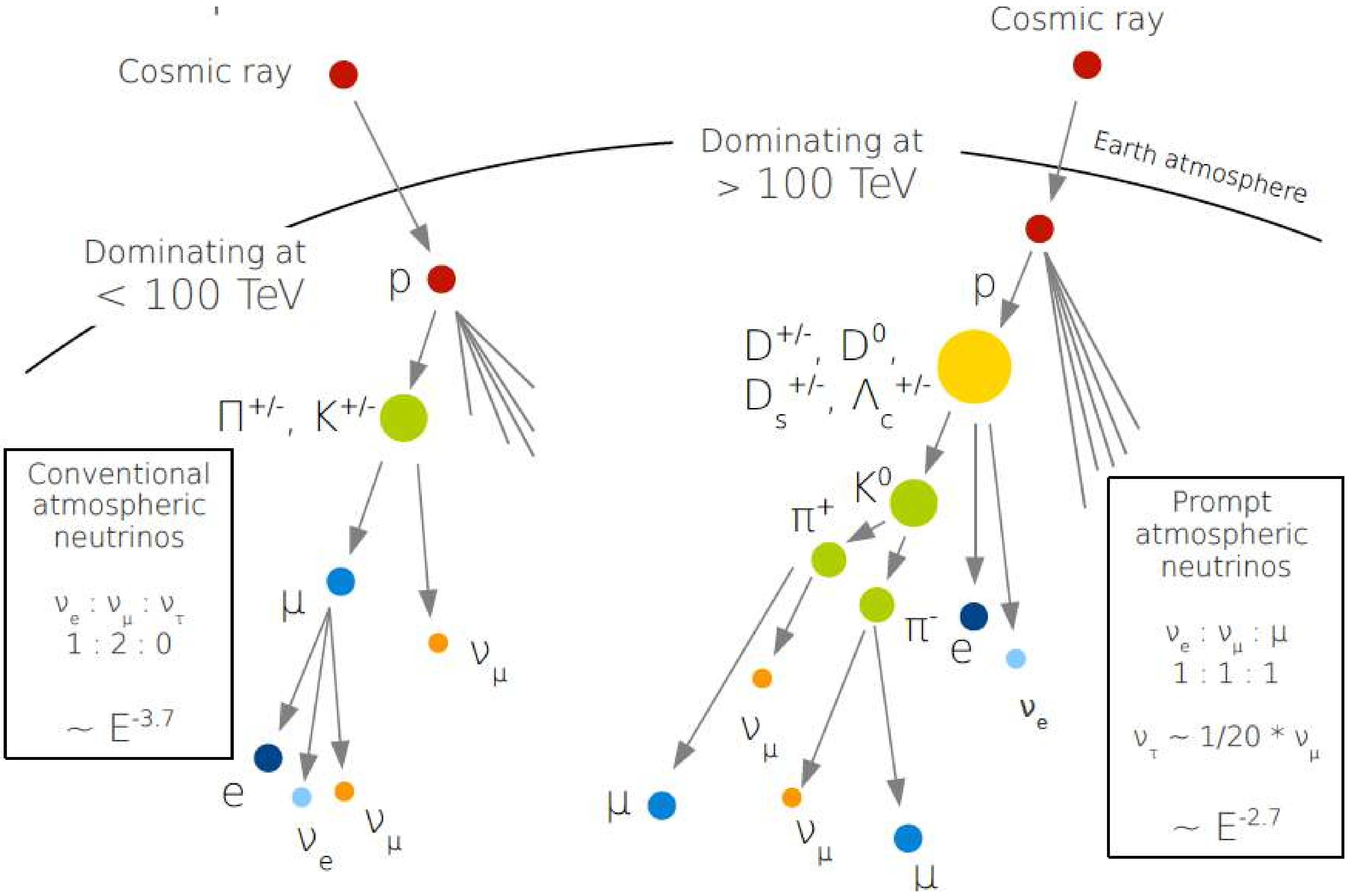
Neutrinos are excellent messengers. They are neutral particles that rarely interact with matter and point back to their sources.

100 THOUSAND ATMOSPHERIC NEUTRINOS

Cosmic rays are charged particles whose paths are bent by magnetic fields. Cosmic ray interactions in the atmosphere produce neutrinos and muons.

100 BILLION ATMOSPHERIC MUONS

icecube.wisc.edu



Conventional atmospheric neutrinos

$\nu_e : \nu_\mu : \nu_\tau$
1 : 2 : 0

$\sim E^{-3.7}$

Prompt atmospheric neutrinos

$\nu_e : \nu_\mu : \mu$
1 : 1 : 1

$\nu_\tau \sim 1/20 * \nu_\mu$

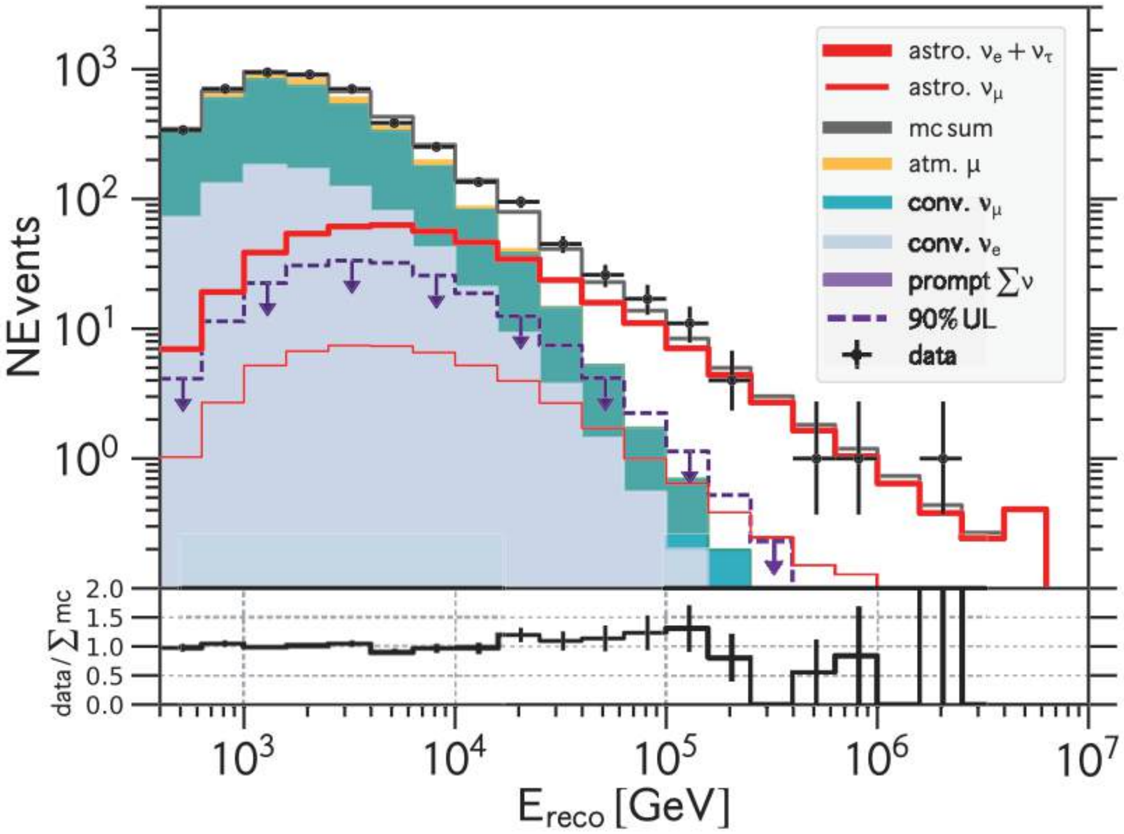
$\sim E^{-2.7}$

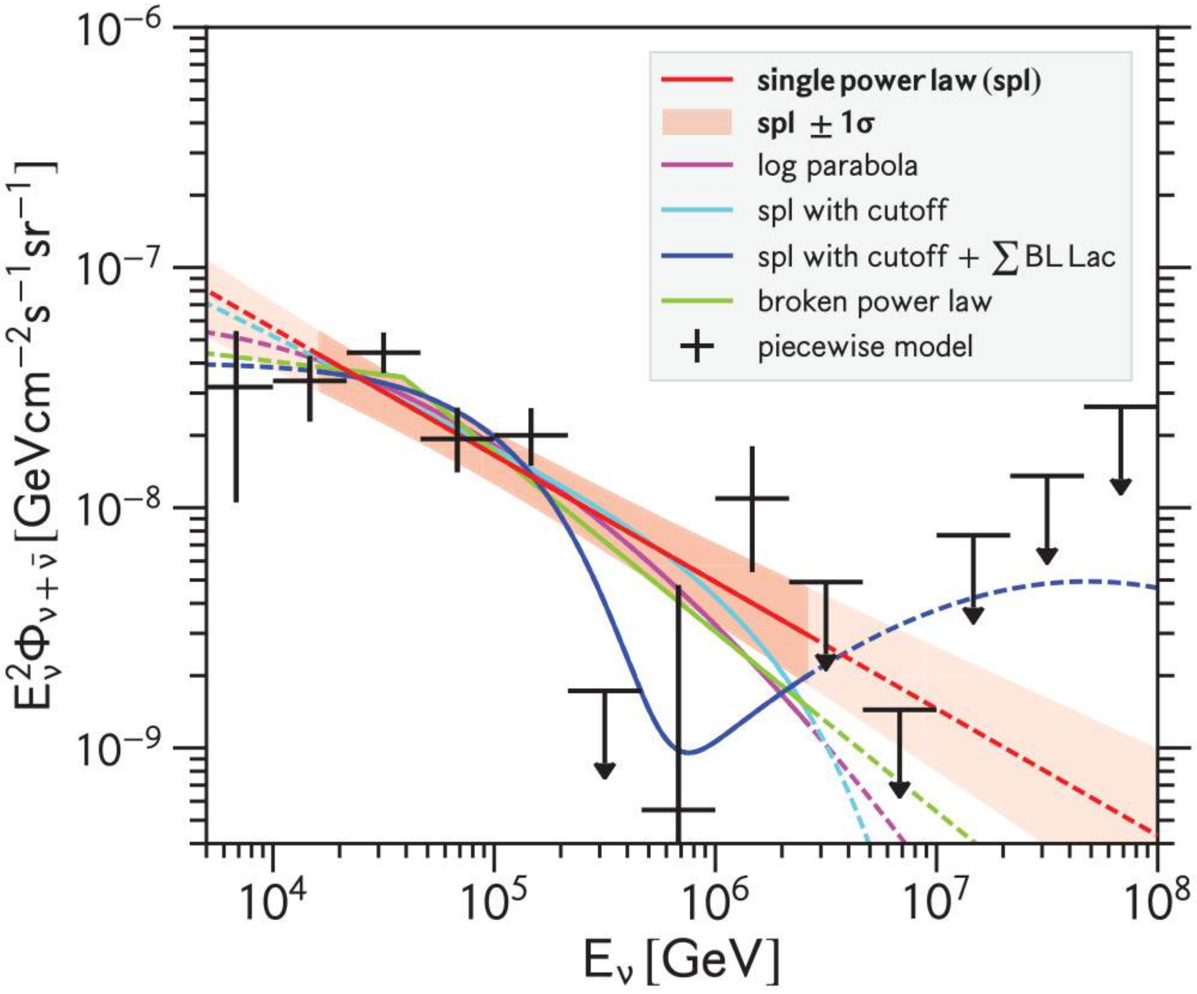
Courtesy: Anne Schukraft

Why is the atmospheric prompt flux important for neutrino telescopes?

The astrophysical ν flux can be fitted by a power-law, broken power-law, spline with a cut-off, log-parabola …

Need to discriminate between these in order to identify the source(s) – but this requires better estimate of atmospheric background



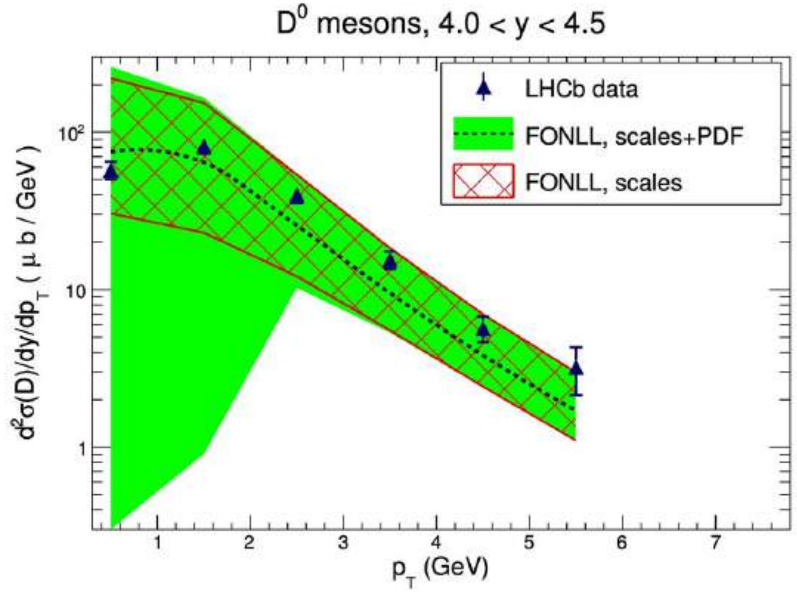


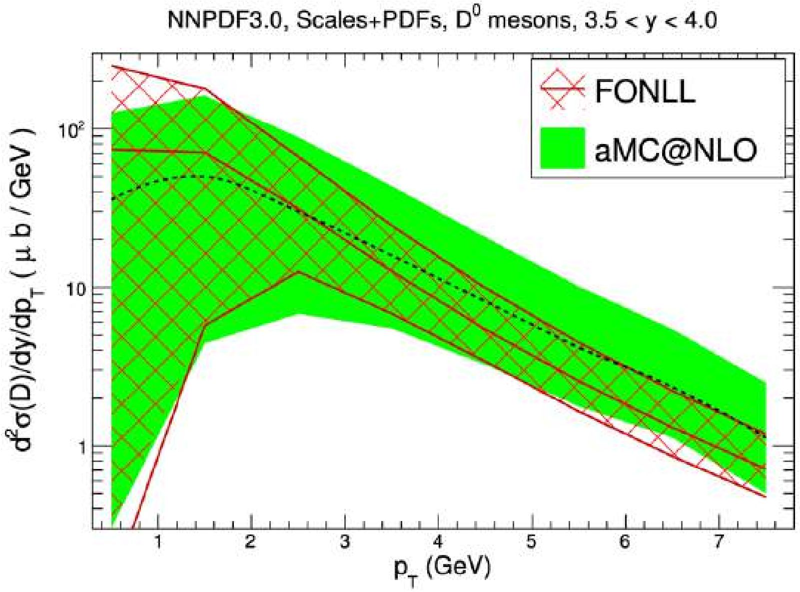
Aartsen *et al*, *PRL* **125**:121104,2020

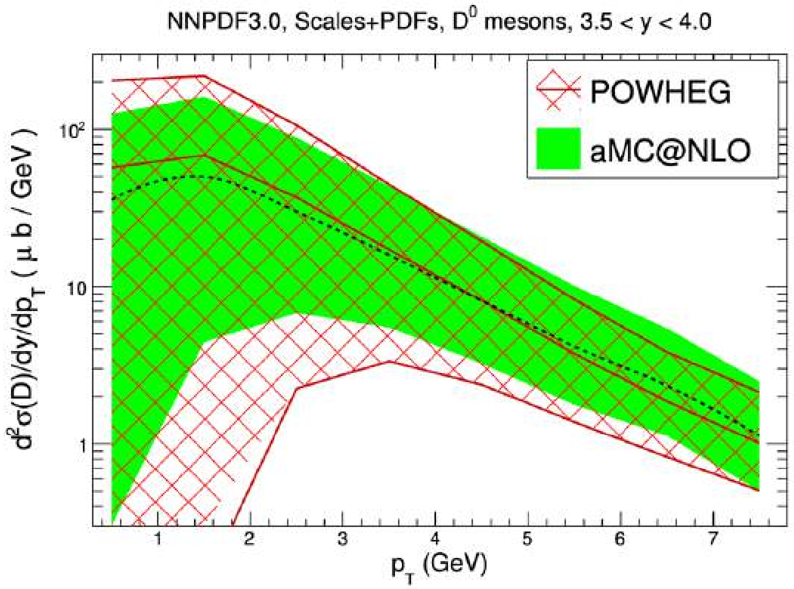
To measure this at an accelerator requires:
$\sqrt{s} = \sqrt{2E_\nu m_p} \simeq 10$ TeV, for $E_\nu \sim 10^7$ GeV: **LHC**
$x_{1,2} \sim (m_c/\sqrt{s})\, e^{\pm\eta} \Rightarrow \eta \sim$ 7-9: **Forward detector**

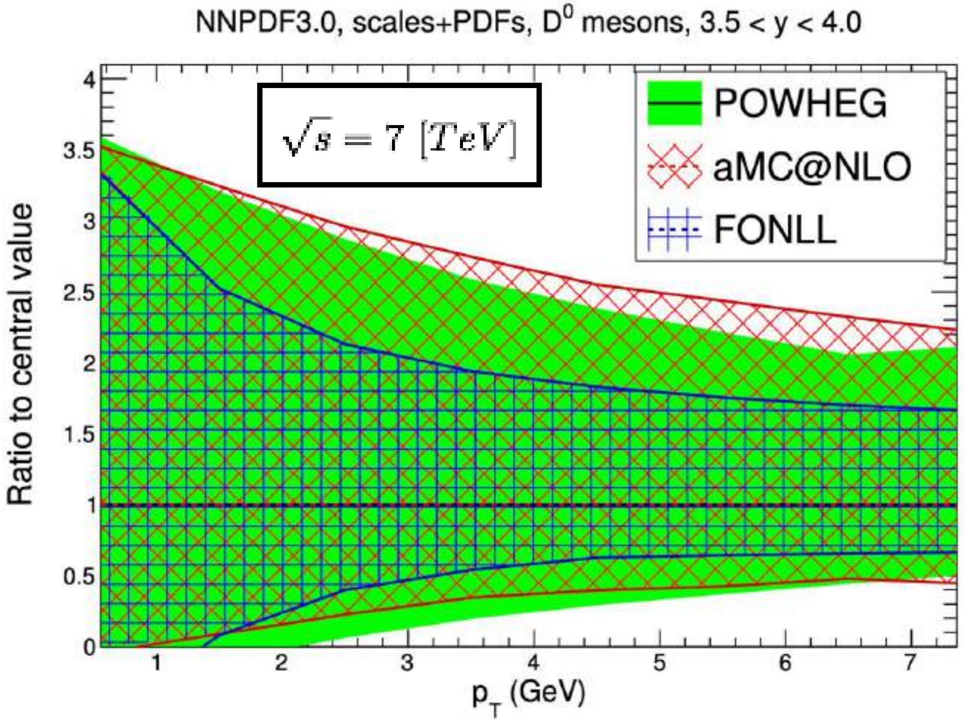
NLO predictions for forward charm production validated with LHCb

LHCb collab. *NPB* **871**:1,2013



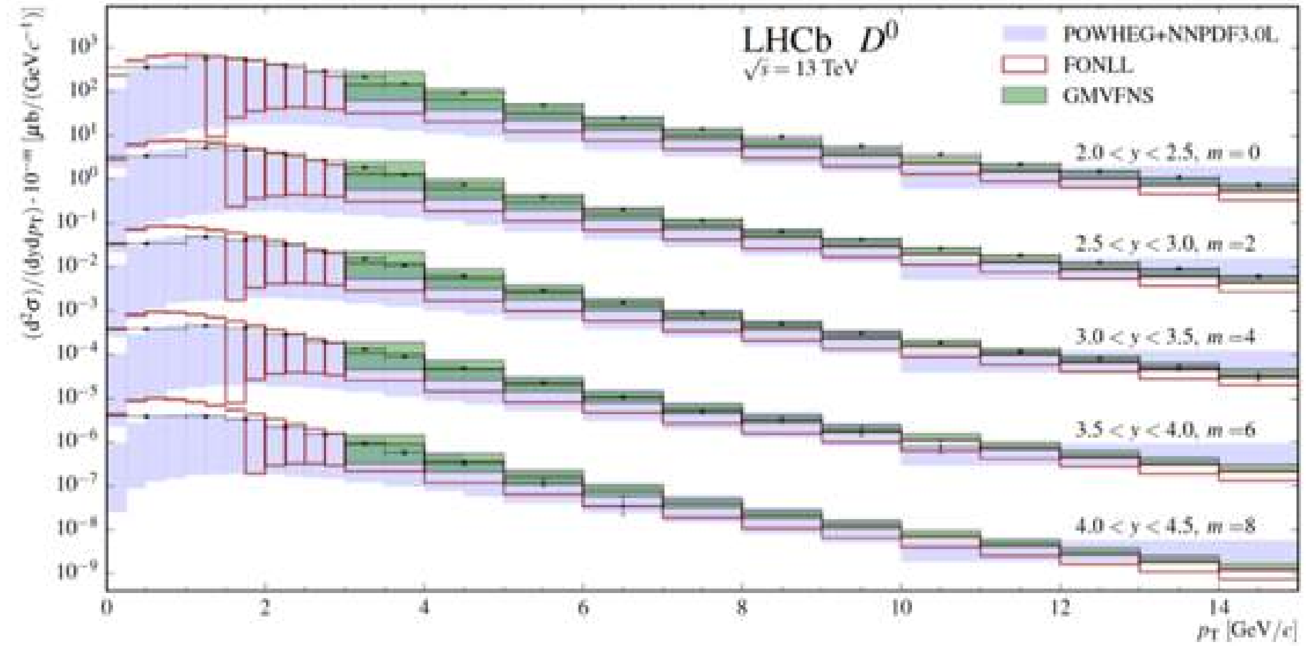




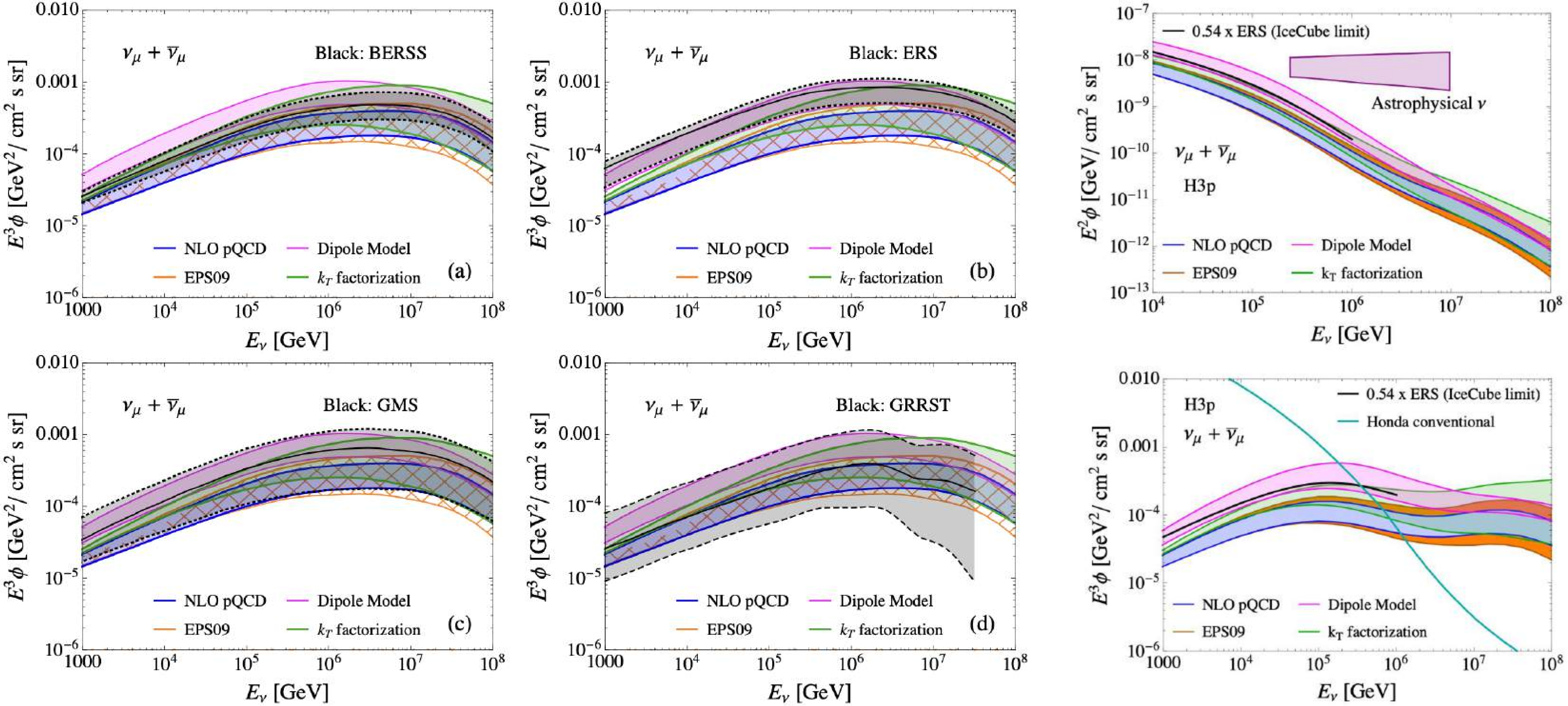


Gauld *et al*, *JHEP* **11**:009,2015

Prediction for 13 TeV matched the data



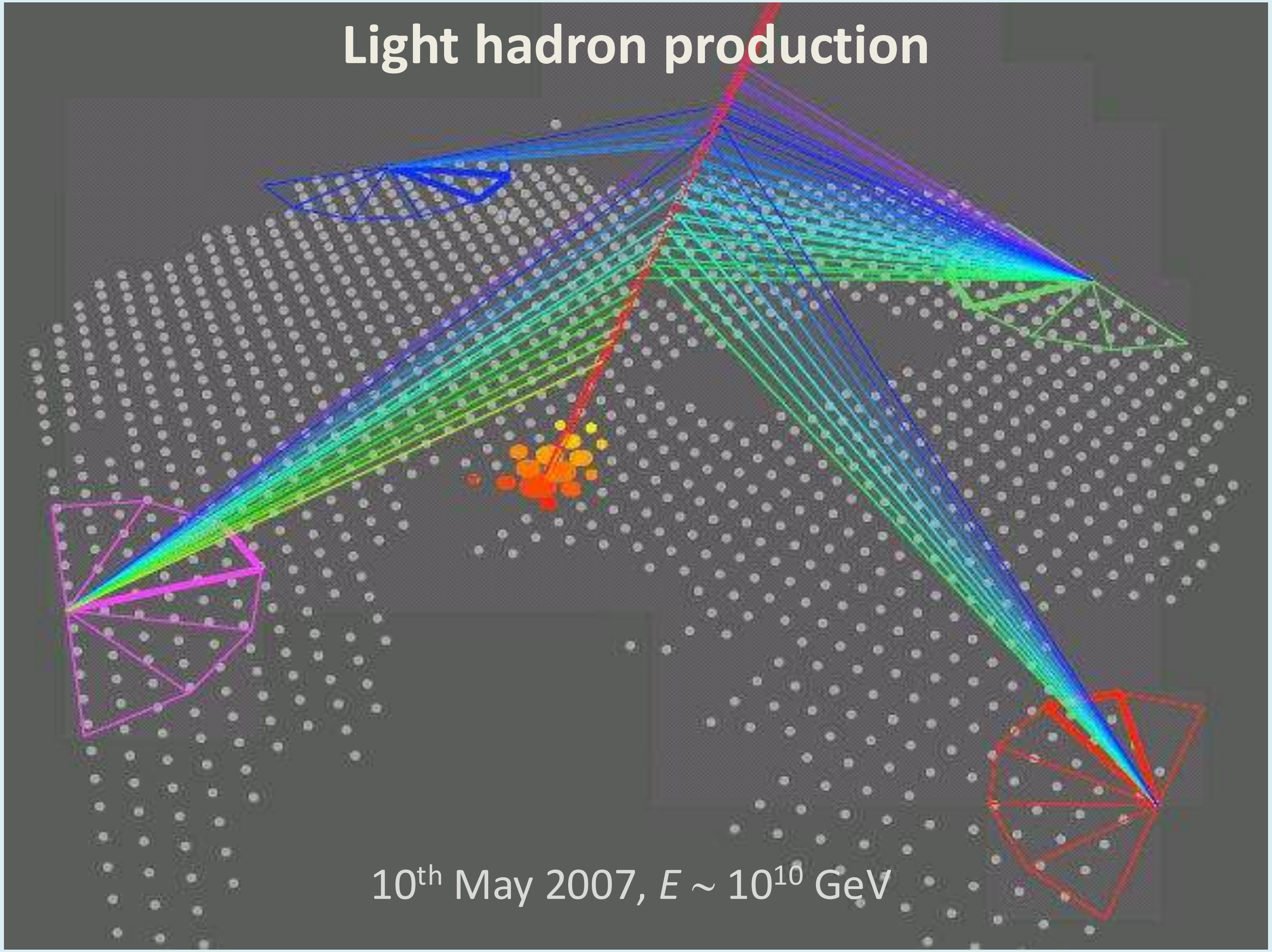
Prediction of atmospheric prompt flux improved with input from LHCb



Bhattacharya *et al*, *JHEP* 11:167,2016

FASERν & SND@LHC will measure the prompt neutrinos in an even *more* forward region (|*y*| > 7.2) than LHCb can access and reduce the uncertainties even further

Light hadron production

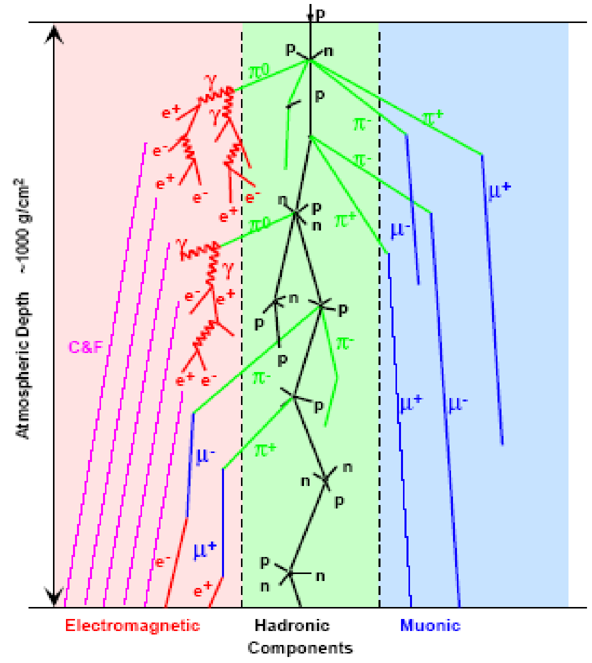


10th May 2007, $E \sim 10^{10}$ GeV

Synergy with Cosmic Ray Air Shower arrays:

Pierre Auger Observatory, IceTop, KASCADE-GRANDE, NEVOD-DECOR, SUGAR, Telescope Array, TUNKA, Yakutsk …

Schematic Shower Development



Fluorescence & Cherenkov-Light (isotropic) (forward peaked)

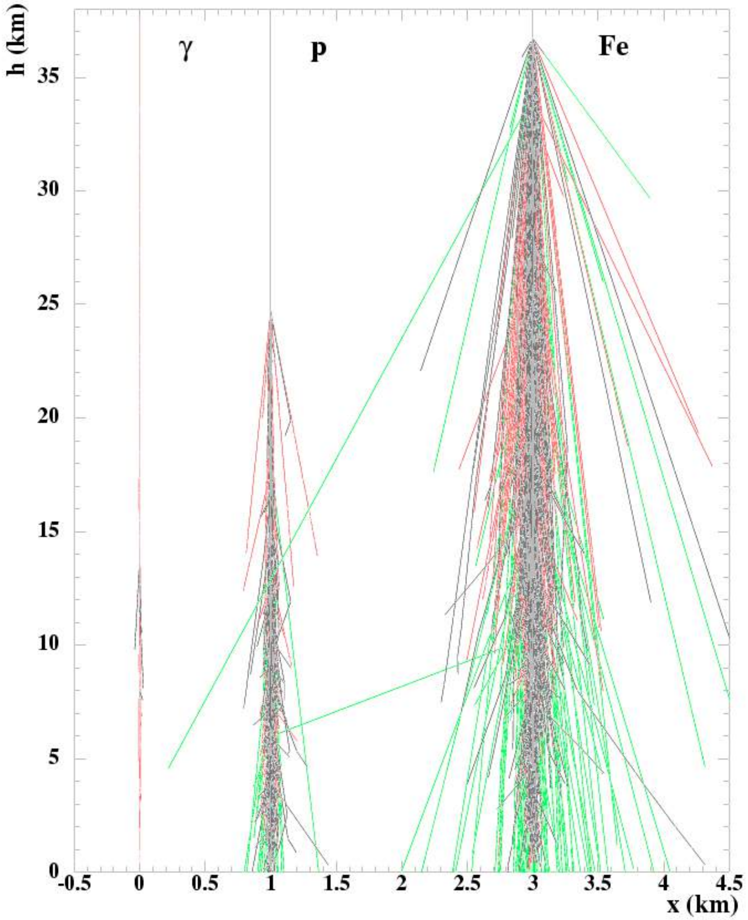
p, n, π : near shower axis
μ, e, γ : widely spread

e, γ : from π^0, μ decays ~ 10 MeV
μ : from $\pi^\pm$, K, ... decays ~ 1 GeV

$N_{e,\gamma}$: N_μ ~ 10 ... 100 varying with core distance, energy, mass, Θ, ...

Details depend on:
interaction cross-sections,
hadronic and el.mag. particle production,
decays, transport, ...
at energies well above man-made accelerators

Complex interplay with many correlations
requires MC simulations

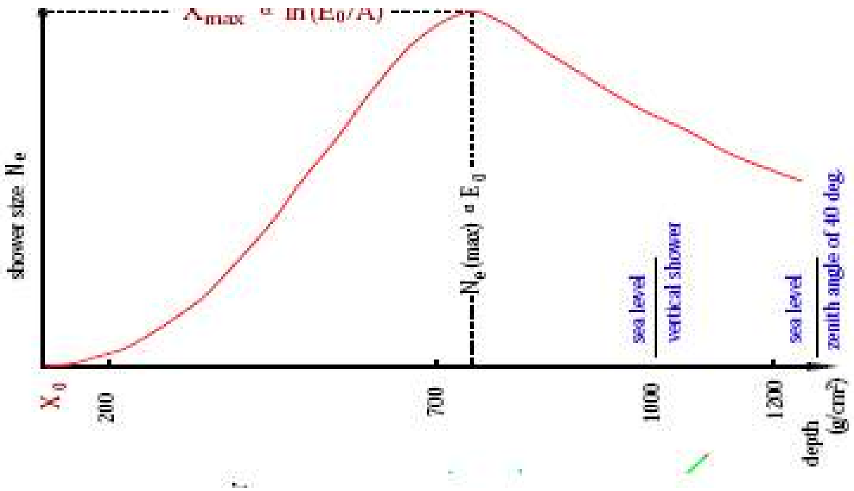


Courtesy: Johannes Knapp

Main sources of uncertainty

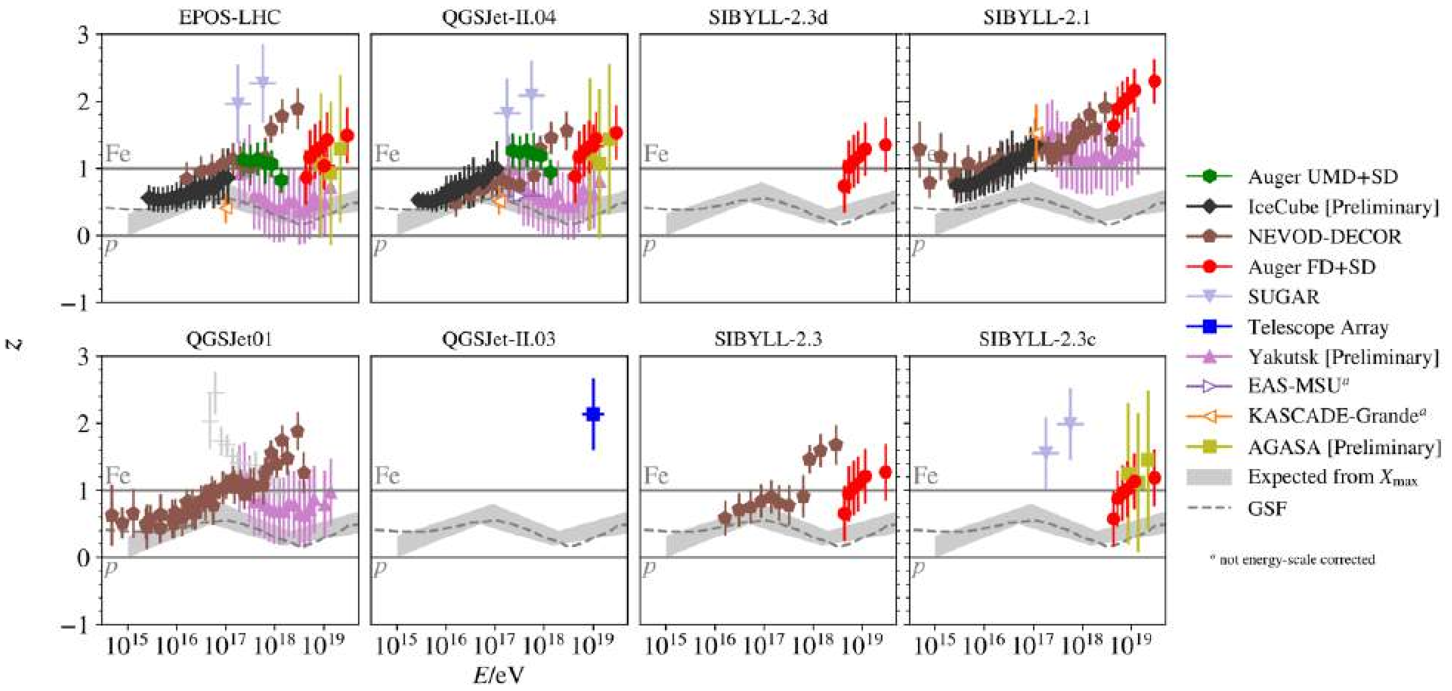
- ➢ Minijet cross-section (parton densities, range of applicability)
- ➢ Transverse profile function (total #-secn, multiplicity distribution)
- ➢ Energy dependence of leading particle production
- ➢ Role of nuclear effects (saturation, stopping power, QGP)

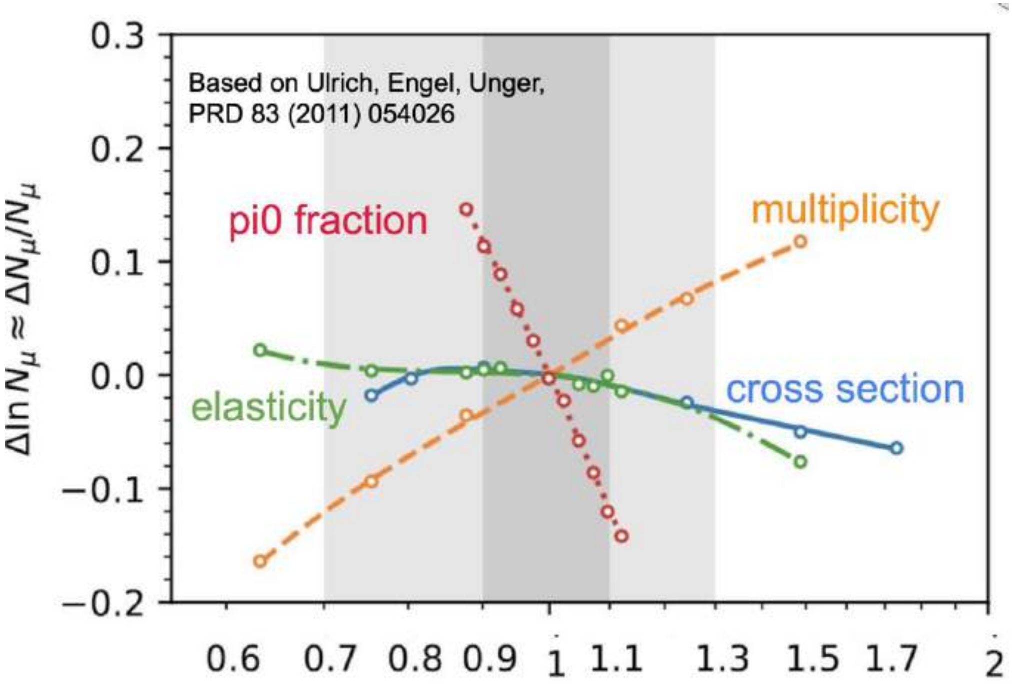
Need input from forward physics experiments



The Cosmic ray muon anomaly – new physics?

Albrecht *et al*, Astrophys.Space.Sci. **367**:27,2022

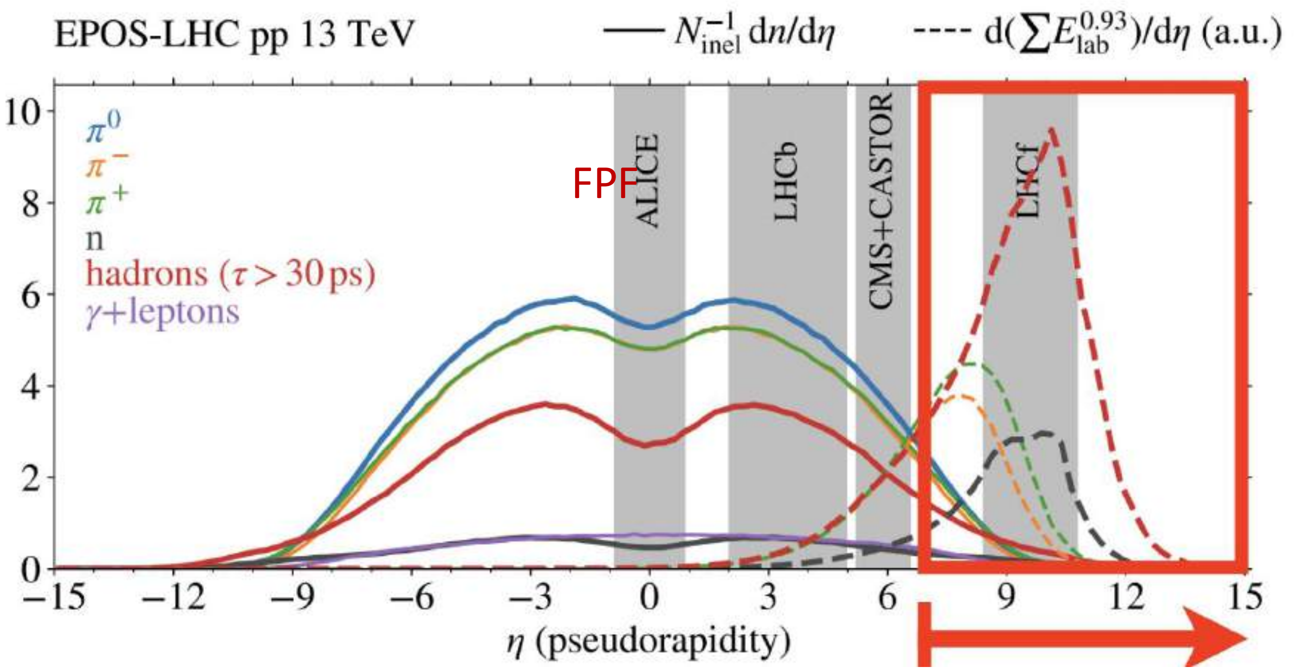




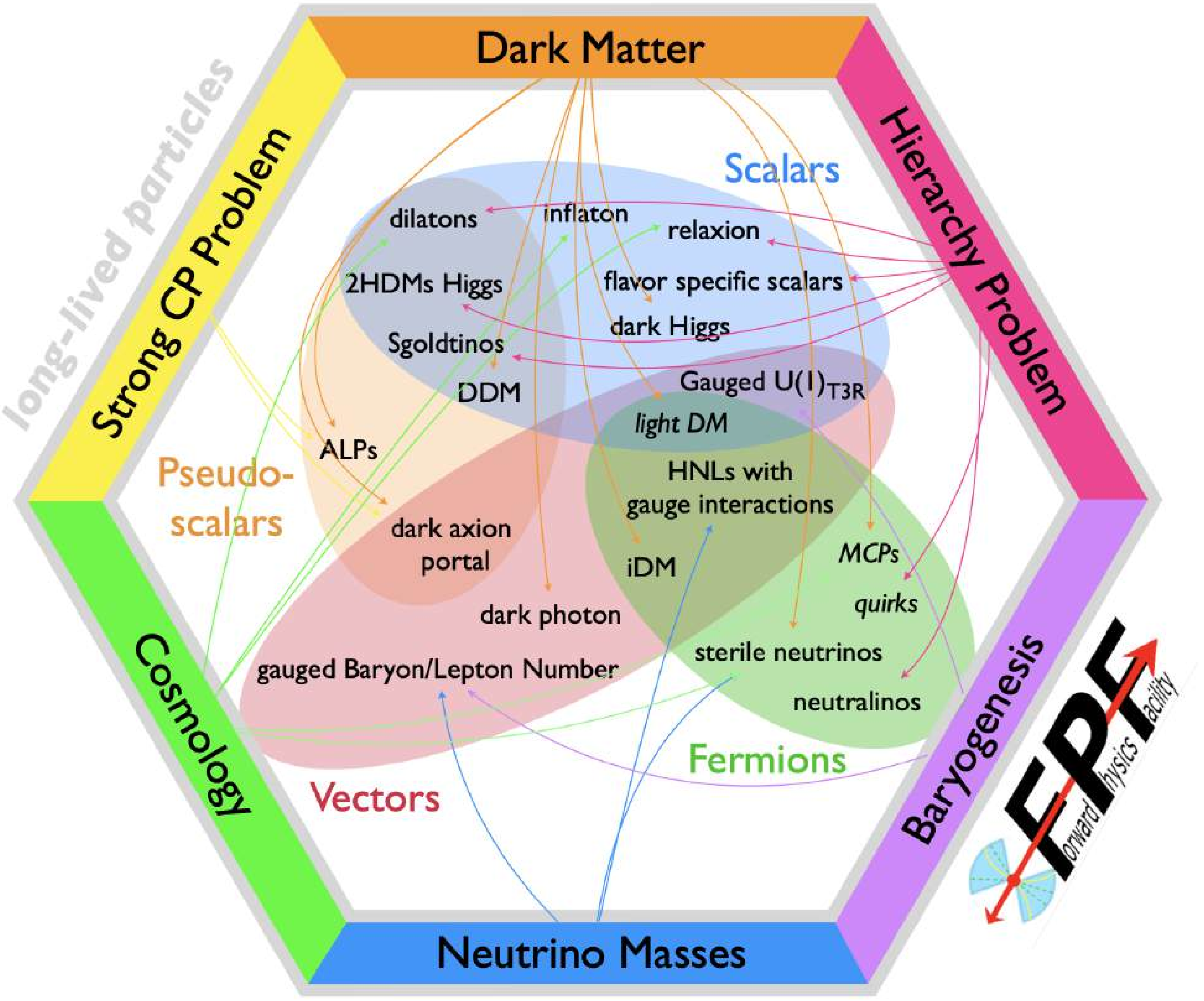
~30-60% mismatch between the observed muon flux and simulations

Difficult to explain away by tuning parameters without introducing other discrepancies with cosmic ray data

The FPF will measure forward light hadron production in a kinematic range never before explored and *definitively* settle the issue



New particles



Synergy with dark matter search experiments

Theoretical motivations for New Light Feebly Interacting/Long-Lived Particles

Standard Model

Abelian, unbroken
Electromagnetism $U(1)_{EM}$

Abelian, spontaneously broken
Hypercharge $U(1)_Y$

Non-Abelian, spontaneously broken
Weak $SU(2)_L$

Non-Abelian, dynamically broken
QCD $SU(3)_c$

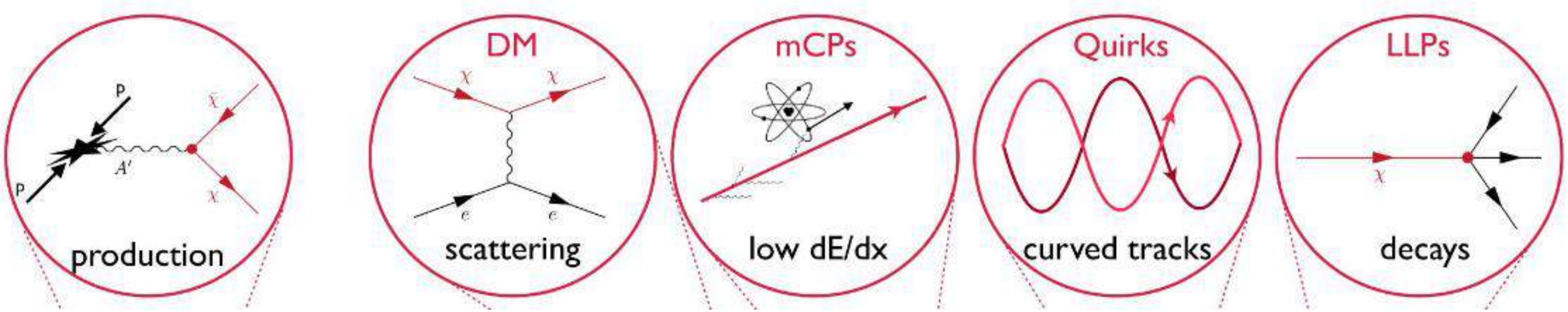
Dark Sector

Abelian, unbroken
Millicharged particles (FORMOSA)

Abelian, spontaneously broken
Dark photon *B*-*L*, L_μ-L_τ gauge bosons
(FASER2, FASERn2, AdvSND, FLArE)

Non-Abelian, spontaneously broken ?

Non-Abelian, dynamically broken
Quirks (FASER2, FLArE)

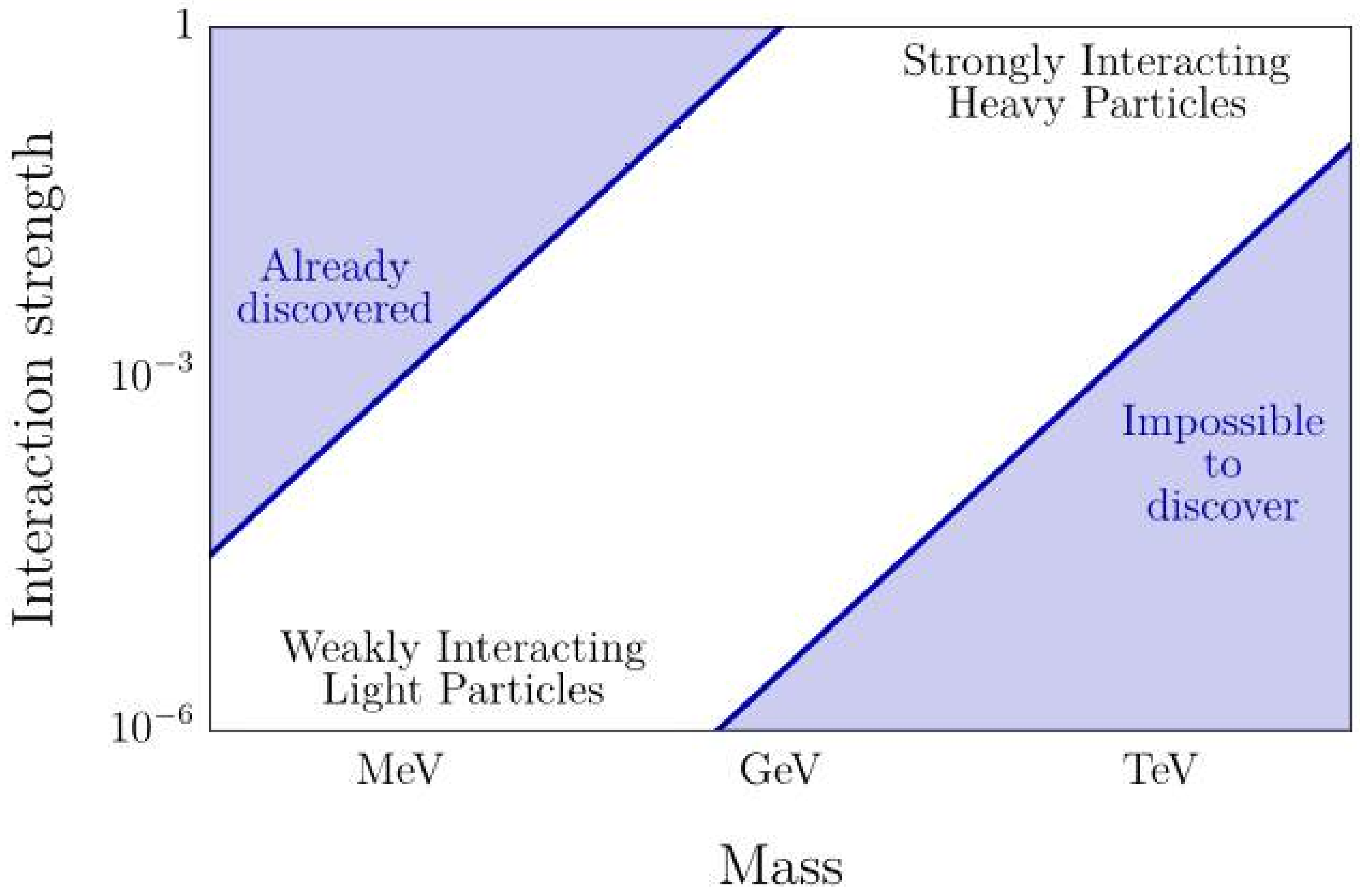


The Portal Formalism

$$\mathcal{L}_{\text{portal}} = \sum O_{\text{SM}} \times O_{\text{DS}}$$

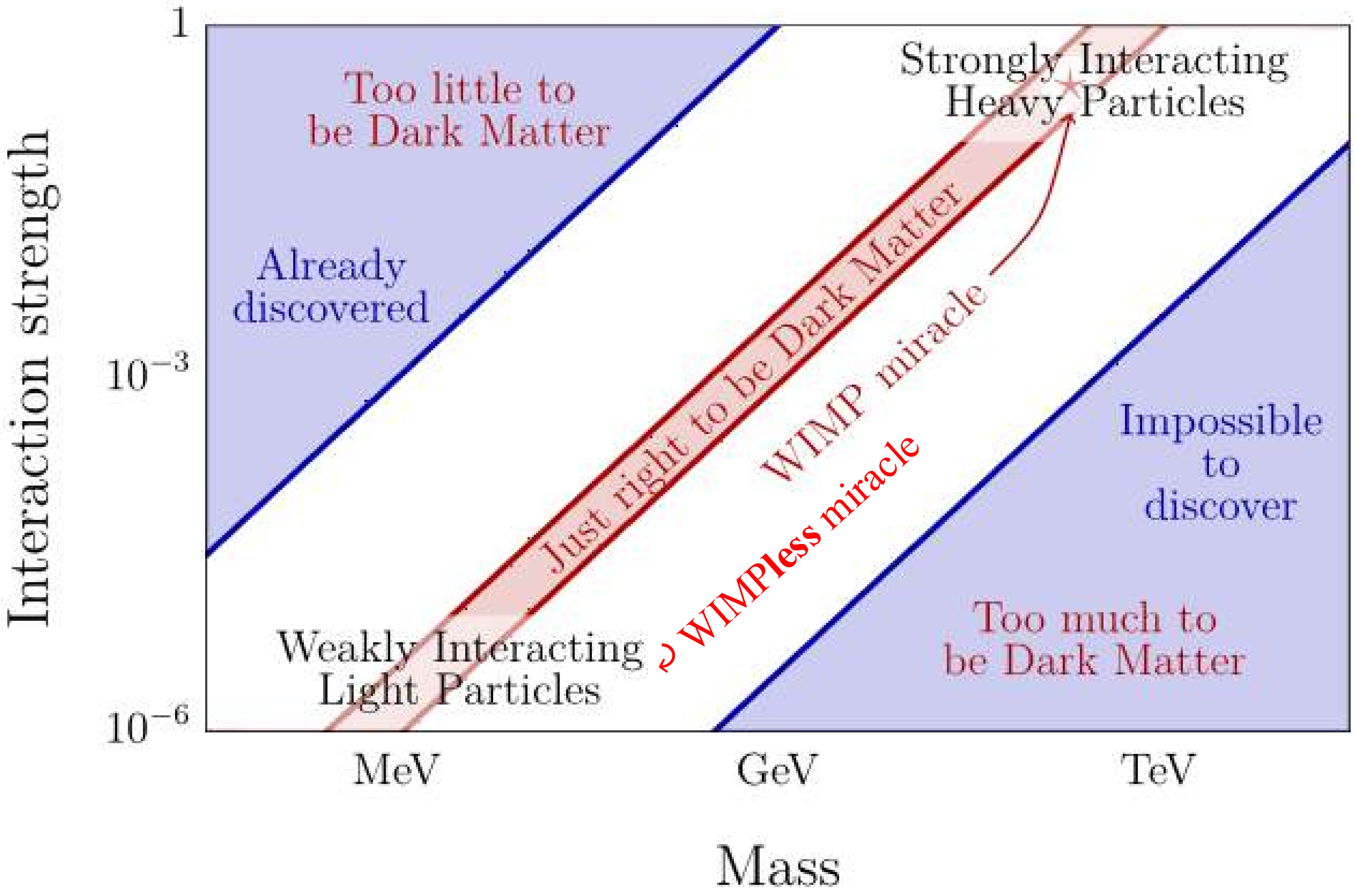
Vector portal	$F'_{\mu\nu} F^{\mu\nu}$	
Scalar portal	$\phi H^\dagger H$	$\phi^2 H^\dagger H$
Neutrino portal	$L H N$	
Axion portal	$\frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$	

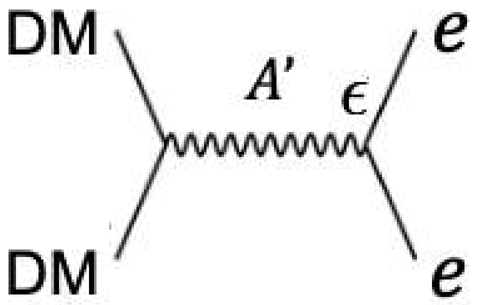
The new particle landscape



- ATLAS & CMS are designed to find new heavy particles which are produced nearly and rest and decay isotropically
- New light particles are produced mainly along the beam, so disappear through the holes that let the beams in …
- We need a detector to cover blind spots in the forward region (FPF) … or do a beam dump experiment (SHiP)

Dark Matter: THE ‘WIMP-LESS MIRACLE’



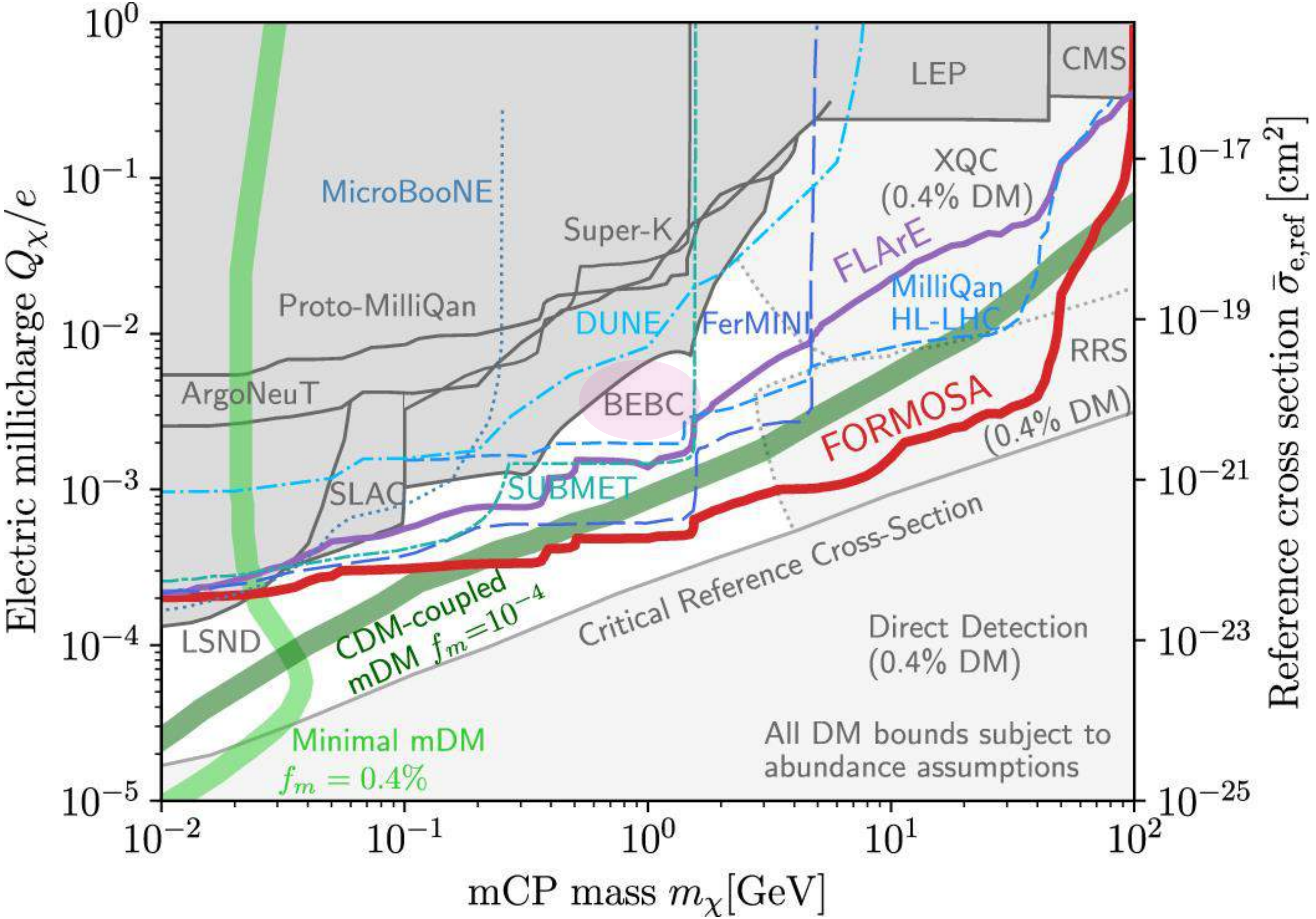


$$\langle \sigma v \rangle \sim \epsilon^2 / m_{A'}^2$$

$$\Omega_{\mathrm{DM}} \propto 1/\langle \sigma v \rangle \sim m_{A'}^2 / \epsilon^2$$

Feng & Kumar, *Phys.Rev.Lett.* 101:231301,2008

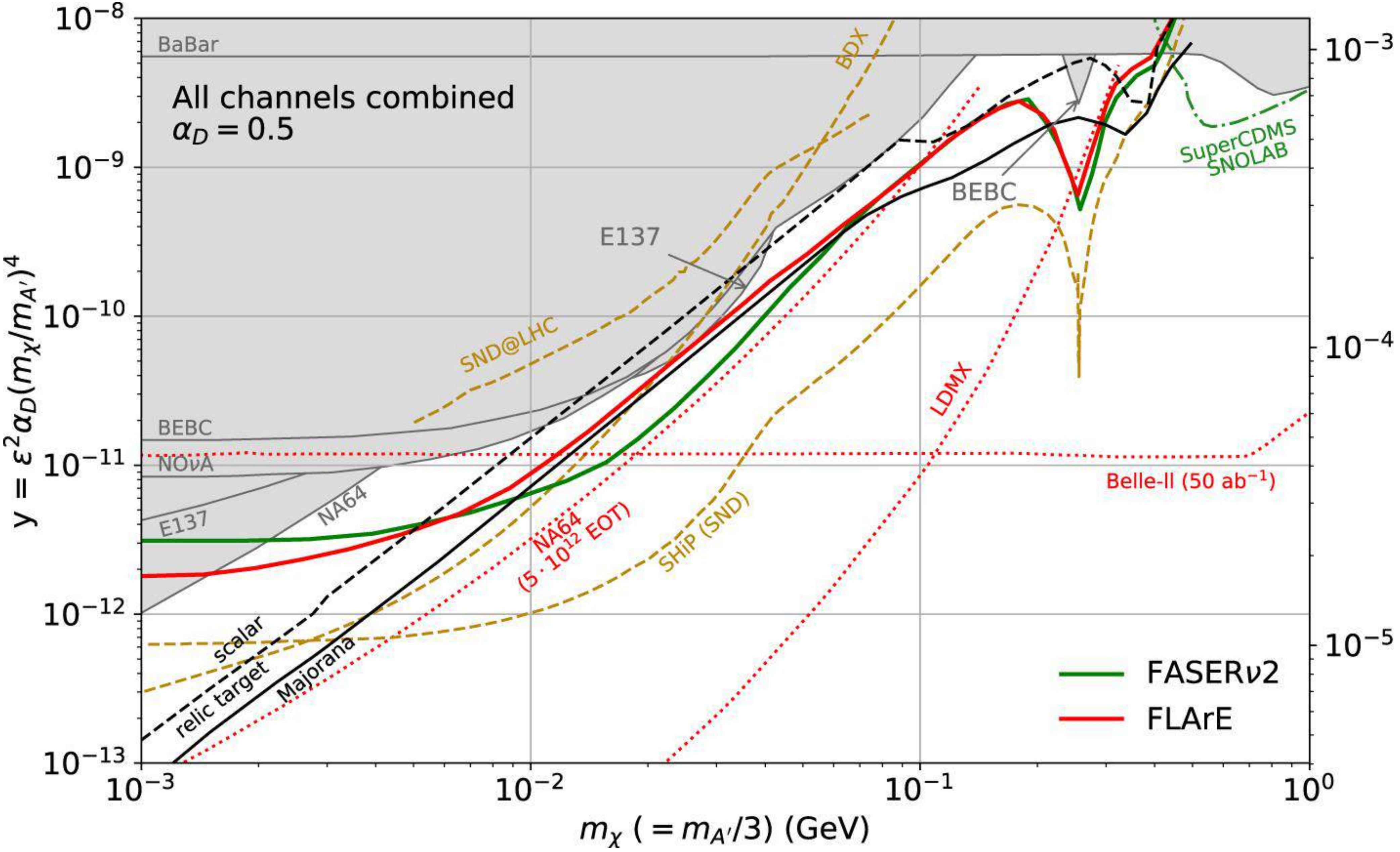
The search for milli-charged particles



Anchordoqui *et al*, *Phys.Rep*.**968**:1,2020

Present bounds on mCPs (grey): LSND, ArgoNeuT, SLAC, Super-K (limit on diffuse SN ν bkgd), LEP, CMS, BEBC
Expected sensitivities for FORMOSA, FLArE; **Projections** for SUBMET, FerMINI, MilliQan @ HL-LHC, DUNE

The search for sub-GeV DM



Batell *et al*, *Phys.Rev.*D**104**:035036,2021

Projected reach for **SHiP** (@ SPS with $6x10^{20}$ POT) and for **FASERν2, FLArE-10** (@ HL-LHC with 3 ab^{-1} integrated luminosity)

conclusions

- There is well-motivated new physics to be explored using high energy neutrinos
- These experiments cost little (< 100 MCHF) but are of great interest to a large (astro)particle community
- Beam dump experiments have in the past proved very successful – SHiP will continue this tradition!
- The Forward Physics Facility will explore *both* SM and BSM physics at the HL-LHC … it ought to be part of the forward planning for the FCC (arXiv:2409.02163)

Message for ECFA

Seen at café outside Royal Tombs @ Αἰγαί)